Avdelningen för Byggnadsfysik
Examensarbete TVBH-5074
Lund 2014

Life-cycle assessment of Photovaltaic systems

- Analysis of environmental impact from the production of PV system including solar panels produced by Gaia Solar

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ISRN LUTVDG/TVBH-14/5074--SE(149)

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Summary

The purpose of this study is to conduct a stand-alone life cycle assessment (LCA) intended for the solar panel manufacturers Gaia Solar. Even though the LCA is stand-alone, the methodology and guidelines for performing such a study on a photovoltaic (PV) system are standardized in order to enable comparison of results with other studies in that field. The life cycle assessment is conducted by ISO standards and IEA PVPS standards specified for PV systems.

LCA is used for identification of all processes for a product or service throughout their entire lifespan, from cradle to grave. It includes all production or/and process stages in order to identify and clarify which contribute to highest environmental impact results.

The goal is to identify which parts and processes of the PV system that contribute to highest environmental impact. Such results clarify the production impacts and can thus be used to prioritize eventual improvements correctly. The environmental impact categories are resource consumption, water use, land use, cumulative energy demand, renewable energy, non-renewable energy, global warming potential, acidification potential, eutrophication potential, ozone depletion potential, human toxicity potential and ionizing radiation. Beyond mentioned environmental impact categories, the study also presents the energy pay-back time, a scenario for extended PV system lifetime, a scenario with thinner solar cells and CO_2 migration potential for Danish electricity mix.

The study is based on data from a LCA database called Ecoinvent. No LCA software was used and all the data was instead managed in Microsoft EXCEL. Available data in Ecoinvent originated predominantly from 2005 to 2006 and therefore does not represent top modern PV system production facilities. This is due to the lack of free new data in an open LCA database.

The functional unit (FU) of the study is 1 kWh produced electricity from converted solar irradiation. The reference flow, which is the size of the PV system, is 3 000 Wp (watt peak). The study also presents degradation of the PV system which leads to falling electricity generation with time.

The results show that one part, of many included in a PV system, contributed to the highest extent to the majority of the impact categories. This part is the solar cells which totally dominated the results for 9 categories out of the 12. The only impact categories that were not dominated by the production process of solar cells were categories related to resources and toxicity. The weight of the solar cells, and thus the required raw materials, are very small in comparison to other parts of the PV system and therefore the solar cells results were not highest in these categories. The results also showed how energy intensive the solar cell production was, and since many impact categories are correlated with fossil fuel combustion for energy purposes, they were overwhelmingly represented by the solar cell.

The energy payback time for the PV system was calculated to 2,5 years for Danish conditions regarding solar irradiation and electricity mix. The case for the extended lifetime of the PV system to 40 years, from previous 30 years, resulted in 23% reduction of all results. The thinner solar cells also contributed to significant improvements in the results varying from 2-23% depending on the environmental impact category.

Based on the results, the part contributing to highest overall environmental impact was the solar cell and this part should be prioritized during potential improvement plans. Every small reduction in the solar cell production process resulted in significant reduction of the total results for the whole PV system.

Preface

This is a master thesis in Environmental Engineering, part of the Civil Engineering education at the Faculty of Engineering, Lund University (LTH), in Lund. This study has been conducted at the department of Building Physics at the Faculty of Engineering, Lund University. This study is conducted for Gaia Solar, producers of photovoltaic panels and systems.

Supervisor for this study has been Elisabeth Kjellsson, PhD in engineering at the department of Building Physics. Representative and supervisor from Gaia Solar was Jesper Frausig. The examiner was Jesper Arfvidsson, professor and head of department for Building Physics at the Faculty of Engineering, Lund University.

May-2014

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1. Introduction

In today's world, energy is undeniably one of the key features for our society to function and thrive. It is included in almost every aspect of everyday events, everything from eating your produced food to watching TV, from traveling to work to having a comfortable indoor environment. By acknowledging the great importance on energy in today's society one cannot help to speculate in how the energy demand will be like in the near or far future. With highest probability the demand of energy will raise a lot in our near future although the magnitude of this increase varies slightly depending on the source one uses to find these prognoses[1]. Either way, an increase is inevitable according to all trustworthy sources. The prognoses, based on political decisions and subsidies, will promote the renewable energy sources so that they can be competitive against fossil fuels leading to a prudential increase of renewable power generators in the total world energy mix[2].

Energy is formed from different kind of sources where many of them are unarguably not sustainable and contribute to many direct and indirect negative effects on the society such as air pollution, increase of greenhouse gases and many more will be mentioned further on in this report. Other sources are more suitable from a pollution and smog point of view but still unsustainable like fossil gases, and then there are energy sources which are both sustainable and clean. Solar power, wind power and hydro power are all examples of sustainable and clean energy. By harvesting the free energy that is surrounding us like the sun's irradiation, wind, biological and water, the amount of renewable energy could replace part of the energy from fossil fuels. This doesn't mean that the environmental impact from these renewable energy power generators also is harmless and sustainable.

Every product and service is based on actions and in turn on energy and resources. Some may get confused that wind, solar and hydro power can have negative consequences on the surrounding ecosystems because of the fact that they are renewable and sustainable, but that is only valid for sun and wind power in the operation stage. The pre-stage and post-stage, also known as production and deposition, are rarely taken into consideration. Fortunately there is a suitable tool for measuring and comparing the effects of products and services from the start to the finish or from cradle to grave in other words. This tool is called LCA, short for Life-cycle Assessment.

1.1 Disposition

This study begins with basic introduction and description about solar power, Gaia Solar, LCA methodology and clarification of the studied system. This is intended to familiarize the reader with the studied subject as well as how LCA is performed.

The next chapter defines the goal and scope of the study and introduces technical aspects most of which have been described in the previous chapter. The study follows an escalating trend with repeating titles in different chapters. The difference is that every chapter increases the depth and complexity of presented information, eventually leading to the results and interpretation before drawing conclusions at the end.

The study also includes a large Appendix chapter due to large amount of data from Ecoinvent LCA database along with calculations, tables and metadata.

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[1] IEA, World Energy Outlook, http://www.iea.org/media/files/WEO2013_factsheets.pdf
[2] ibid.

1.2 Background

Life-cycle Assessment is relatively new method compared to the total length of the industrialized era. LCA identifies the environmental impact of different products, processes, services and the key stage where they occur, for example production, usage or disposal[3]. The first popular LCA study was conducted by Coca Cola back in 1969 which aimed to show and identify that all containers contributed to an impact on the environment but with different magnitude[4]. By studying the obtained results Coca Cola could execute an important strategic move and begin to recycle aluminum cans and thereby lowering the impact of excavating and treating new aluminum compared to treating the used cans. The Coca Cola LCA surely made and impact of the view on environmental impact assessment and process identification amongst other companies by the cheer popularity of Coca Cola Company.

At that time and up to 1990, different approaches of identifying and solving problems amongst companies production stages emerged but they focused and exposed different parts of the prediction line in combination with having different aims and methods. In 1990 the Society on Environmental Toxicology and Chemistry (SETAC) first used the term Life-cycle Assessment at a world workshop and in 1993 the International Organization for Standardization begun working on standardization of LCA which was complete in 1997 and is known as Life cycle Assessment – Principles and Framework ISO 14040. Almost one decade later in 2006, another document was released, which was based on several standardized documents, to result in ISO 14044 Life cycle Assessment – Requirements and Guidelines[5]. These guidelines are vital for the correct approach that companies should make when conducting a LCA in order to obtain a comparative and trustworthy study.

Many companies today are interested in conducting their own LCA's and also demand that their providers downstream do the same[6]. At the same time many customers upstream desire LCA results. Not having a LCA could be a deal breaker for some customers depending on their niche. According to EEA, Life cycle Assessment is not only a tool for minimizing the impact on the environment but also for business to cut costs and become more compatible[7].

LCA is not the only useful tool for making decisions regarding a product, service or process. There are also economic and social analyses[8] that need to be considered in order to whey all categories and make a reasonable decision. Lowering the environmental impact as much as possible is perhaps possible for a given product, service or process but the cost for such accomplishment can be great and irrational for a company.

[3]Ecomii, *Coca-Cola dilemma*, 2014, retrieved 14 May 2014, <http://www.ecomii.com/building/coca-cola-dilemma>

[4] PE International Sustainability Performance, *A brief history of life cycle assessment (LCA)*, 2014, retrieved 14 May 2014, <http://www.pe-international.com/company/newsroom/news-detail/article/a-brief-history-of-life-cycle-assessment-lca/>

[5] ibid.

[6] EEA, *Life cycle assessment – a guide to approaches, experiences and information sources*, 2014, retrieved 14 May 2014, <http://www.epa.gov/nrmrl/std/lca/pdfs/Issue20report20No206.pdf>

[7] Ibid., p. 9-11,

[8] ISO 14 040, *Environmental management - Life cycle assessment - Principles and framework*, 2006, p. 9

1.3 Gaia Solar

Gaia Solar is a company located in Copenhagen, Denmark and was established in 1996[9]. Gaia solar produces several different solar panels but are famous for their flexibility and creativity when it comes to satisfying customers. The company specifies in producing aesthetic solar panels that attract and open opportunities for new and more attractive solutions. Highly customized aesthetical solar panels can outcompete ordinary solar panels in many situations where aesthetics is of importance such as urban buildings, hotels, offices, museums, schools and more. Gaia Solar have successfully overcome the obstacle of dull and boring standard solar panels by offering the customer a wide variety of modules with different shapes, colors other features.

Their products can also be installed in many ways enhancing the practical and aesthetical features. Solar panels can be installed on façade or in facades, on roofs or integrated in the roofs, they can be made for shading on windows and buss stations for example, and the solar panels can be ground mounted as well.

1.4 Purpose

The purpose of this study is to conduct an internal Life cycle assessment for Gaia Solar on one of their solar panel models, the Design Line 145 (DL 145). Costumers such as architects are seeking aesthetical and customized solutions. Many architects and other customers embrace development of building sustainability and green housing[10,11]. In turn, energy is a vital factor for a comfortable household and thus a major field for improvement. With that said, according to Gaia Solar more and more customers seek a LCA that goes hand in hand with their sustainable motives. For the environmentally friendly customer a LCA is a good environmental impact benchmark for the solar panel, which in turn can be compared to other solar panel LCA's.

Gaia Solar was in need of LCA, both for their own information and for the customers, and that is the reason why this study is carried out. The study is of importance for identifying the impacts throughout the whole cradle-to-grave process.

The study will also provide and highlight the stages from the whole production chain with highest environmental impact which the company then can improve and eventually benefit of. The processes with highest environmental impact can be at a stage out of reach for Gaia Solar for example at the extraction of silica step or refinement of silica or other step along the solar panel production line. The information will still be of importance for Gaia Solar not just because it affects the final result of this LCA but also because the company can choose to influence their suppliers to modify their production chain, lowering the environmental impact or finding alternative suppliers with different production method and lower environmental impact.

[9] Gaia Solar, *Hvem er Gaia Solar*, 2014, retrived 14 maj -14, <http://www.gaiasolar.dk/dk/om-gaia-solar/

[10] The initiative for renewable energy in architecture, 2008, retrieved 14 May 2014, <http://www.rearch.umn.edu/>

[11] Sweden green building council, *GreenBuilding – certifikat i energibesparing och energieffektivisering*, 2014, retrieved 14 May 2014, <http://www.sgbc.se/certifieringssystem/greenbuilding>

1.5 Production at Gaia Solar

Gaia Solar produces solar panels but to obtain a complete solar panel, there are many steps involved, all of which will be included in this Life cycle Assessment. As many companies, Gaia Solar specialize in one bit of the product puzzle, which in their case is assembly of complete solar cells into solar panels and further providing whole PV (photovoltaic) system to the customers. Complete, ready to use, sub-parts that are included in the PV system are provided by different suppliers which in turn specialize in these steps that Gaia Solar does not.

The solar panel that is included in this study is produced by Gaia Solar and is called Design Line 145. It is a square panel containing 36 solar cells and is approximately 1 m^2 module. Unlike common solar panels, no aluminum frame is incorporated into the DL 145 panels, and the necessity of an aluminum frame is overcome in a different way.

Energy use for the assembly process at Gaia Solar originates from measured assembly data in IEA PVPS Task 12 report. The assembly at Gaia Solar and results presented in the mentioned IEA study are assumed to be identical. The assembly process will be described further on.

1.6 LCA methodology

Conducting a LCA is not an easy task, especially when LCA software is not used. All inflows and outflows trough the chain from cradle to grave like energy, resources and emissions to different areas all leading to the environmental impact assessment, have to be accounted for. By defining the goal and scope, outlining the system boundaries, data quality and more, one can obtain very different result[12]. The standardized LCA by the ISO 14 040 – Principles and Frameworks, specifies how a correct LCA should be performed. The four main phases of a Life Cycle Assessment are Goal and Scope, Inventory Analysis, Impact Assessment and Interpretation are shown below in figure 1. The figure also includes a stage (on the right side) for the motives of why a LCA can be conducted.

[12] Rydh C.J. et.al., *Livscykelanalys, en metod för miljöbedömning av produkter och tjänster*, 2002, p. 49-50

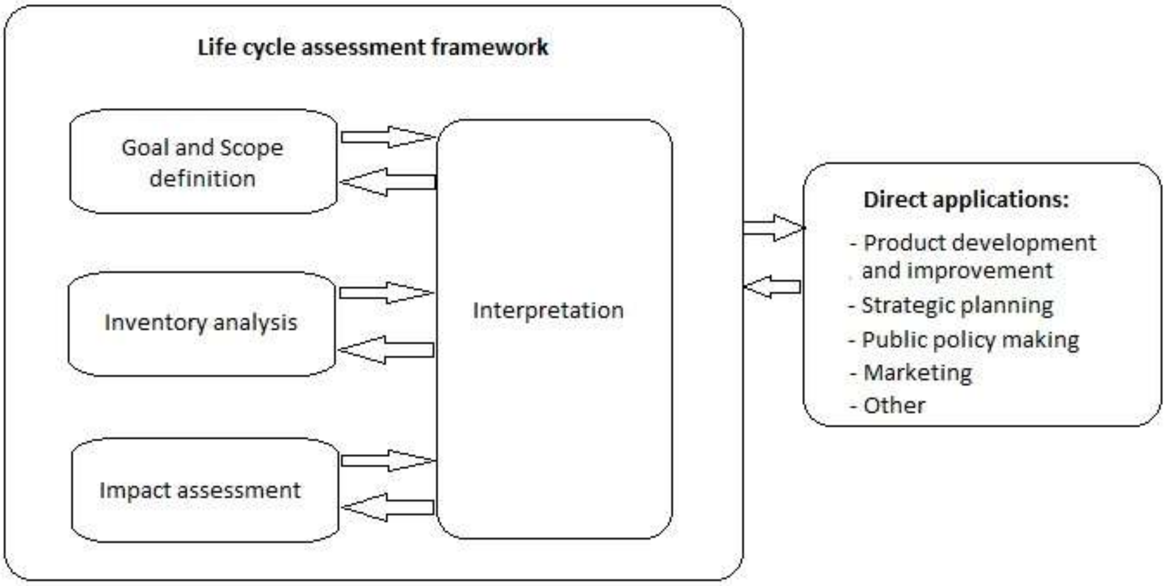

Figure 1: A chart showing the different stages in a LCA and their interconnection. Source: ISO 14 040 - Environmental Management - Life Cycle Assessment - Principles and Framework.

When conducting a LCA, specifically about solar power, there is another document of great importance since it specifies guidelines for LCA for photovoltaic systems. The document is called Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, Task 12, Subtask 20 Life cycle assessment, and is produced by IEA (International Energy Agency) PVPS (Photovoltaic Power System Programme).

The following section, 1.6.1 – 1.6.5, only describes typical aspects and chapters that are often included in a LCA. It also describes the methodology of these aspects but does not actually present them. Goal and Scope methodology is presented in section 1.6.2 but the actual Goal and Scope definition for this study is presented in section 2. The same is valid for the remaining sections, 1.6.3 – 1.6.5, but their respective actual definition and presentation sections are chapter 3, 4 and 5.

1.6.1 IEA-PVPS-TASK 12 Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity

The PVPS (Photovoltaic Power System Programme) is a part of IEA (International Energy Agency)[13]. PVPS is included in various projects concerning the conversion of solar energy to electricity. Their main purpose is as quoted:

"*to enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option*".

It contains methodology guidelines for conducting a Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA) for grid-connected photovoltaic systems, which is exactly what this study for Gaia

[13] Fthenakis, V. et. al., IEA – PVPS – Task 12, *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 2011, p. i

Solar is about. The document clearly states that it is based on ISO 14 040 and ISO 14 044 guidelines which still apply to LCA concerning photovoltaic electricity. The document contains specific recommendations for PV, which otherwise conducted only by ISO 14 040 and ISO 14 044 would give the author of the LCA large room for own assumptions and system boundaries and this in turn will lead to widely varying results. It can be said that IEA PVPS is a harmonization PV LCA where the result of various LCA studies can be reasonably compared with each other. The report presents guidelines for the following aspects[14]:

- life time of a PV module
- structure
- cables
- invertors
- irradiation
- performance ratio
- degradation
- system boundaries
- function unit
- impact categories
- energy pay-back time
- CO_2 migration
- Energy mix

All the recommendations will be considered in this study as far as it is possible. Assumptions stated in the document Task 12, Subtask 20 will also be taken into account unless real data is available.

1.6.2 Goal and Scope

This section only describes typical aspects that are often included in the Goal and Sope of a LCA. The actual definition of Goal and Scope is presented further on in section 2.

The goal should describe the following[15]:

- why the study is carried out
- what the results will be used for
- for whom the results are intended

There can be for several reasons for conducting a LCA like strategic planning for product development, necessity for different labeling, satisfying customers and comparison of products. The definition of the goal also affects the depth and width of the scope meaning, which steps need to be included to fulfill the goal of the study[16].

The scope is clarification of what is included in the study to fulfill the goal and what is not. It describes the width and depth of the study. The scope includes titles like:

[14] ibid., chapter 3
[15] Rydh, J.C. et.al., op.cit. p 49-50
[16] ISO 14 044, *Environmental management – Life cycle assessment – requirements and guidelines*, 2006, p. 11

Initial flowchart is a helpful way to visualize the simplified system that is studied.

Options to model defines whish product or products are studied and if the LCA is a stand-alone (no comparison intended) or a comparative system. The later requires technical data and methodology to ensure that a comparison can be made or even a framework for common products[17].

Function Unit (FU) is the reference unit that enables studies to be compared. The unit is a quantified measure of the system's performance or service. All flows in the flowchart, which in turn represent the stages of production that the system requires in order to produce the product or service, are also quantified and presented in that unit. The function unit is also of importance when preforming a comparative LCA[18]. Paint, for example, has a covering function which can be compared with other alternative methods to achieve the same service, to cover. These can be spray, sticker, metal sheet and more, which all have the same function and can thus be compared. The function unit for such a purpose is for example $1m^2$ of covered wall. There can also be a secondary function as well. For instance paint also result in good aesthetics[19].

The **Reference flow** in the case of painting can be a house of certain dimensions. For PV studies, reference flows refer to the size of the system that quantifies the functional unit[20].

Impact Categories describe what environment impact sectors should be studied in the LCA. According to the ISO standardized documents, it should include:

- human health
- resource use
- ecological consequences

These are in turn more specialized and contain many more subcategories. The subcategories are for instance acidification, eutrophication, toxic compounds, ozone depletion, resource depletion and more[21]. The categories will be fully reported further in the section 2, Goal and Scope.

Elementary Flows describes the flows within the system based on the different impact categories. For example one should be able to see what amount of CO2-equivalent is released between two steps in the process in order to understand the contribution to Global Warming Potential (GWP) from that step and also the lifetime of the gases in the atmosphere. Obviously there are several compounds that contribute to the category GWP like methane, carbon dioxide, carbon monoxide, nitrous oxide and chlorofluorocarbon (CH_4, CO_2, CO, N_2O, CFC). All of these are converted to one main compound that represents the specific impact category, in this case Global Warming Potential. In another impact category like acidification there are other contributing compounds that are in turn converted to the representative compound for that category. The conversion step is based on the effect of one compound on the category in relation to the reference compound, also called equivalent[22]. CH_4 is thus converted to CO_2-equivalents and to account for its greater effect on the environment it is multiplied by 25. Scientific experiments determine that CH_4 is 25 times stronger greenhouse gas than CO_2 and

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17 Baumann, H. et.al., *The Hitch Hikers Guide to LCA, an orientation in life cycle assessment methodology and application*, 2004, p.75
18 ibid., p. 33
19 Prof. Joillet, O., et.al., Science network, *Life cycle assessment – lecture 2*, www.sciencenetwork.com/**lca**/lesson_2.pps
20 Jungbluth, N., et.al., *Ecoinvent- report No.6, part XII*, Swiss center for Life Cycle Inventories, Dübendorf, CH, 2009, p. 48
21 Baumann, H. et.al., op.cit., p.139
22 ibid., p. 140

there are likewise conversion numbers for all other compounds related to their respective representative compound of a certain category[23].

System Boundaries determines the processes that should be included in the studied system. The boundaries are for practical reason so that the project doesn't get carried away in calculating infinitive amount of processes, but only the relevant ones with highest importance to the product. The most correct LCA will be the one which includes all steps and processes of the product and thus do not have boundaries at all, but that is impossible to conduct[24]. System boundaries need to be described in different levels such as[25]:

- Boundaries to natural systems
- Boundaries to geographical systems
- Time boundaries
- Boundaries relative to other products

Cut-off Criteria describes rules and assumptions that could be made when dealing with the inflows to the system and what and how much can be cut off from the system. EPD (Environmental Product Declaration) states that most often all flow-data are included if information is available but if necessary (no available data) there are small margins to cut but the excluded parts still need to be reported and clearly stated that they are cut-off. Generally 1% of the total environmental impact, mass or energy can be cut off. The cut-off should also be motivated with expertise judgment and be justified. This means that the results must first be obtained and then to apply cut-off method[26].

Data Quality is according to ISO 14 044 meant to be specified so that the goal and scope are met. It also states that data quality requirements in a LCA aimed to the public should be of greatest quality and include every step stated by ISO 14 044 section 4.2.3.6.2[27]. The table below presents and categorizes these steps.

Table 1: Data quality requirement steps presented by categories. Source: Rhyd, C.J, et.at., 2002

Relevance	**Reliability**	**Accessibility**
Time-related coverage	Precision	Reproducibility
Geographical coverage	Consistency	Consistency
Technology coverage		
Completeness		
Representativeness		

Furthermore the documentation of both qualitative and quantitative data in the inventory is vital for the assessment of the data quality[28]. For further description of the presented steps in the table above, see the ISO-document, ISO 14 044, 2006 *environmental management – life cycle assessment – requirements and guidelines*, section 4.2.3.6.2.

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[23] Climate change connection, *CO_2-equivalents*, 2009, retrieved 14 May 2014, <http://www.climatechangeconnection.org/emissions/CO2_equivalents.htm>
[24] Rydh, C.J., et.al., op.cit., p 53
[25] Baumann, H. et.al., op.cit., p. 79
[26] EPD, *supporting annexes for environmental product declaration*, version 1, 2008, retrieved 14 May 2014, <http://www.environdec.com/Documents/GPI/EPD_annexes_080229.pdf, sid 7>
[27] ISO 14 044, op.cit., p. 9-10
[28] Rydh, C.J., et.al., op.cit., p. 62

Allocation is also an important step in the LCA and can have big impact on the results[29]. When it comes to determining the environmental impact of a certain product, it is based on all consequences on material and energy input in all stages of the products lifecycle. It seems quite simple but that is the case for a product chain that specifically and only produces one product along the entire chain. In most cases, logically, there are byproduct and/or other products depending on the point of view meaning that if one produces wine glass, the main product is just that and the left over scraps of the glass process are the waste or byproduct. That is certainly the case if the byproducts are scraped/deposited or recycled, but if one would sell the scraps to a company manufacturing fiber glass insulation then the scrap suddenly is assumed to be another product and function beside the wine glass. In that way the glass scraps replace the production of glass scraps at some other plant and thus lower the overall environmental impact[30].

In long production chains of several refining methods, there is high possibility of several products being formed and here is where allocation is a convenient tool to apportion the environmental burden of one product amongst the other products from the same chain[31].

There are different types of allocation that can be applied to a LCA study but it all depends on what type of LCA is conducted and thus links back to the goal of the LCA[32]. According to ISO 14 041 allocation should be avoided by increased level of detail of the model or expanding the system to include all products. Otherwise, if allocation is inevitable, the environmental load should be apportioned among the systems different functions[33].

Major **Assumptions** should be described and explained in the Goal and Scope phase and the same goes to the **Limitations.** Big assumptions occur when for example system expansions are defined and limitation are for example if the study is valid for any location on the planet or not, or if the study is valid for a certain time period[34].

1.6.3 Life cycle inventory (LCI)

During the inventory analysis stage of the LCA, all inflows such as energy, water, material, fuels and more, are identified for the studied system during its lifetime. All the flows leaving the system such as exhaust to air, water and land, product and byproducts are also identified[35]. These in- and outflows from every stream of every part along the production chain, within the defined system, are thereby quantified. The data is vital for the next stage of the LCA which is Impact Assessment[36].

In order to obtain this data, every flow within the system has to be measured, either directly or/and the use of online LCA databases. There are many databases for LCA and one of these, which is also in compliance with IEA PVPS Task-12, is Ecoinvent.

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[29] Baumann H. et al., op.cit., p. 87
[30] ibid., p. 86
[31] ibid., p. 83
[32] ibid., p. 88
[33] ISO 14 041, *Environmental management- Life cycle assessment- Goal and scope definition and inventory analysis*, p. 11
[34] ibid., p. 92
[35] STONE, stonecourses, *Life cycle inventory analysis*, retrieved 14 May 2014, <http://www.stonecourses.net/environment/invlca.html>
[36] ibid.

The collected data is then sorted into categories which are at a later stage sorted out as environmental impact categories[37]. The collected data is then calculated per function unit.

1.6.4 Impact Assessment (Results)

This section deals with the data from the inventory in several ways. The raw data is sorted in different environmental impact categories with the purpose to enable a better oversight and easier assess which emissions contribute to which environmental categories like acidification, global warming potential, ozone depletion potential and more[38,39]. Often the inventory data parameters can be huge, from 50 to 200 parameters, which make it hard to comprehend all the results. By implementing **classification** the raw data form the inventory analysis is sorted out in up to 15 categories enabling a clearer oversight and easier comprehension of the results[40]. Because of the lack of consensus on which categories should be used, there are no certain mandatory categories but generally the impact assessment includes categories such as resource consumption, effects on ecology and human health[41]. Furthermore these categories consist of other categories (may be seen as subcategories to the main three categories) that in turn describe the data in more detailed impacts categories. The process is shown in the image below!

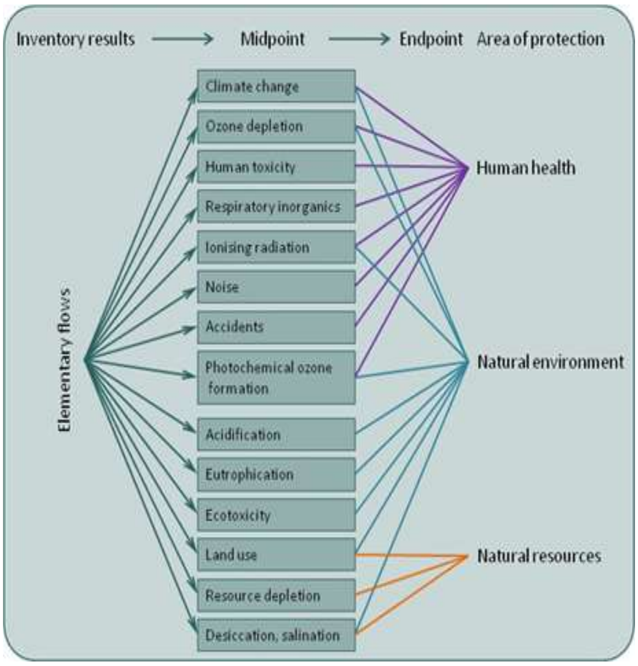

Figure 2: Description of the process of classifying elementary floes from the system into impact categories. Source http://www.thefactsabout.co.uk/content.aspx?pageid=200

[37] Rydh et.al., op.cit., p. 63
[38] Baumann H. et al., op.cit., p. 129
[39] STONE, stonecourse, *Life cycle impact assessment*, retrieved 14 May 2014, <http://www.stonecourses.net/environment/impactlca.html>
[40] Baumann H. et.al., op.cit., p.129
[41] STONE, stonecourse, *Life cycle impact assessment*, retrieved 14 May 2014, <http://www.stonecourses.net/environment/impactlca.html>

It should also be mentioned that an emission compound can be included on several categories because of its tendency to affect several environmental fields. For example the emission of nitrogen oxides can affect environmental categories such as acidification, global warming potential and ozone layer depletion[42].

After the elementary flow data is sorted in different categories, the data is then translated into one single compound representing the whole impact category. This is called **characterisation.** This means that all the compounds have to be adjusted so that they can be presented in the form of the main characterization factor or equivalents as mentioned earlier. For instance, methane (CH_4) which is included in global warming potential category is converted to the characterization equivalent for this category carbon dioxide (CO_2). Since methane has 21 times stronger global warming potential then carbon dioxide, it means that the amount of methane must be multiplied by 21 in order to be presented in carbon dioxide equivalent. The same process is applied to all compounds in all categories.

Weighing is also a method to assess the potential impact. It is meant to aggregate all result into one final presentable number. This method is subjective and there are no agreements on weighing methods but there are examples of methods often used. Because weighing is an subjective method it should only be used in special cases when it has to be[43]. Ecoinvent data includes different impact methods, which will be discussed further on, where data is weighed for certain impact categories. Except weighing conducted by these methods, no other weighing will be made in this study.

1.6.5 Interpretation and discussion

The interpretation section is meant to analyze the results of the LCA and also to explain the limitations as well as making conclusions and recommendations[44]. The results need to be presented in a complete and consistent manner based on the goal and scope of the study[45]. An important interpretation for PV systems is energy pay-back time which is included in IEA PVPS Task 12 Subtask 20 guidelines[46]. Further interpretations of the results and their impacts will be presented in section 5. Interpretation regarding the extended lifetime of the PV system, a scenario for thinner solar cells and the spared greenhouse gas emission due to installation of a PV system, will also be presented further on.

1.7 Manufacturing of crystalline silicon solar panels and parts

The production of a PV system is quite extensive and consists of many sub-products such as solar cells, inverters, glass etc. The including parts of a PV system are described in the following sections.

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[42] Rhyd, C.J., et.al., op.cit., p. 79
[43] ibid., p. 80
[44] Baumann H. et al., op.cit., p. 175-177
[45] World steel association, *Interpretations – Objectives*, 2012, retrieved 14 May 2014, <http://www.steeluniversity.org/content/html/eng/default.asp?catid=146&pageid=2081271783>
[46] Fthenakis, V. et. al., p. 8

1.7.1 Solar cells

Solar cells are the most vital part of a solar panel since they convert the incoming solar irradiance to electricity. There are two kinds of crystalline silicon cells, mono-crystalline and poly-crystalline also referred to as single-crystalline (sc-Si) and multi-crystalline (mc-Si), but the one used by Gaia Solar in the solar panel of interest are mono-crystalline solar cells[47]. The process of acquiring a final functional solar cell is vast and very complicated. A flowchart of this process will be presented further on in the study.

1.7.2 Inverters

The main purpose of the inverter is to convert incoming direct current (DC) electricity from the solar panels into the more commonly used alternating current (AC) used in households and the grid[48]. The inverter also synchronizes the voltage and transforms it to a proper amount such as 230 V in households[49]. Another purpose, in more advanced inverters, is to track and utilize the maximum amount of power from the solar panel by adjusting to the voltage and current input which can vary with time[50]. The power output will thus be optimal. The size of the inverters also depends on the load, meaning that invertor for 3000Wp solar installation will be smaller than an installation of 50 000Wp. There are also micro-inverters that are attached on every single PV panel which enables independence from a whole string of series connected PV panels. This is beneficial because often series connected panels to a central invertor can be disrupted/cut by partial shading or other external cause, leading to deactivation of the whole series connected string[51].

1.7.3 Electric installation

The electric installation enables the flow of converted electricity to be utilized and distributed to the grid. It is included in the panels in form of junction box (connector box output from the solar cells) which enables easy connection on the back side of the panels, and cables witch are connected to the junction box in order to connect a solar array[52].

The electric installation also includes meters and cables to the different electronic parts of the PV system. It also includes a lightning arrester which protects the PV system from lightning[53].

The junction box is a PV connector system that links the cables from one or more PV panels or PV panel strings, to the invertor. It has both functional and aesthetic properties such as organizing input

[47] Jungbluth, N., et.al., op.cit., p. ii.
[48] ABB, *Solar inverters,* 2014, retrieved 14 May 2014, <http://www.abb.com/solarinverters>
[49] Jungbluth, N., et.al., op.cit., p. 101
[50] ABB, op.cit.,
[51] Energy Saving Trust, *Solar inverters*, 2014, retrieved 14 May 2014, <http://www.energysavingtrust.org.uk/Generating-energy/Choosing-a-renewable-technology/Solar-panels-PV/Solar-inverters>
[52] Jungbluth, N., et.al., op.cit., p. 110
[53] ibid.

cables from different panels/panel string, enables for an easier PV panel exchange or connection[54]. The junction box also disables the reverse current at dark conditions and thus protects the solar panels[55].

1.7.4 Slanted roof PV structure installation

PV panels can be mounted in different places and the technique for mounting differs. For example a vertical building integrated PV system is not the same as a ground mounted on and even a roof mounted one. This LCA study is conducted on the assumption that the PV system is mounted on a slanted roof[56] of a one floor villa.

To be able to attach the PV panels to the roof, there has to be a structure in between to hold them firmly connected. This structure is composed of aluminum bars and clamps as well as steel screws and bolts[57].

1.7.5 Encapsulate

Encapsulate for the solar cells, and as a part of the solar panel, contributes to many benefits. Encapsulate is the layer which laminates the solar cells and prevents current leakage, acts as a buffer between the front glass and the solar cells and reduces stress from the glass cover to the solar cells. Not only does it prevent the solar cells from breaking but it also keeps them in place and eliminates the risk of contact separation between the solar cells[58]. Logically an additional layer between the solar cells and the incoming solar irradiance, results in reduced efficiency, but the properties of the thin layer of encapsulate materials minimizes that impact.

1.7.6 Back glass

Back glass is used instead of aluminum frame on some panels such as Gaia Solar's Design Line 145. The glass is ordinary float glass, not coated, and along with the front glass can enable a sandwich type layout which is stable and eliminates the necessity of an aluminum frame.

1.7.7 Front glass

Glass covers provide structural and protective properties for the solar cells and the frame itself. Because the glass is between the electricity producing solar cells and the incoming solar irradiance, they are designed and manufactured in such a way that as much as possible incoming light is passed through the glass cover. There are several different types of glass covers, all designed to optimally contribute to higher electricity production and to suit different customers and different PV

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[54] ELS Spelsberg, *Connecting System For Photovoltaics, 2009/2010.*
[55] DuPont, *Cost-effective photovoltaic junction box housings*, 2014, retrieved 14 May 2014, <http://www.dupont.com/products-and-services/plastics-polymers-resins/thermoplastics/case-studies/pv-junction-box-housings.html>
[56] Jungbluth, N., et.al., op.cit., p. 12
[57] Gaia Solar, *mounting structure*.
[58] STR Holdings Inc, *STR protected benefits*, 2014, retrieved 14 May 2014, < http://www.strsolar.com/str-protected/benefits/>

technologies. Important properties of the glass cover are: high solar energy transmittance and low iron content in the glass, anti-reflective coating (AR-coating) and other techniques to reduce reflectance, increase consistency and durability throughout the solar panel lifetime[59]. The low iron, highly transparent front glass is often treated and coated in order to reduce reflectance. The coating is a whole other process then the front glass, and is presented separately in this study.

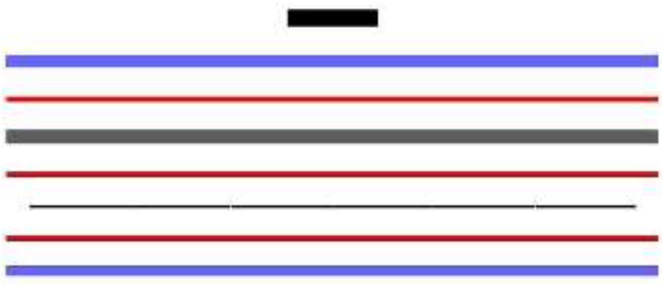

Figure 3: Profile illustration how and what parts are combined in a DL 145 crystalline silicon solar panel. Source: Gaia Solar documents.

1.7.8 Protective back sheet (PBS)

The back sheet of the panel plays a huge role in the long term performance of the solar panel. It protects the solar panel from harsh environments during its lifetime, moisture and is an electronic isolator. At the same time the PBS is durable, UV stabile, light and thin[60], all of these properties contribute to a better solar panel.

1.7.9 Anti-reflective coating (AR-coating)

AR-coating has many applications where reflection is undesirable such as glasses, screens and solar panels. The coating reduced reflection of sunlight and instead allows it to pass through, resulting in higher energy output from the solar panel[61]. A study by NREL (National Renewable Energy Lab) on AR-coatings resulted in an overall performance increase, of a PV module, by up to 3,5-5% under STC (standard testing conditions)[62]. It also acts as a protective layer for the frontal glass because of its properties, allowing the AR-coating to withstand harsh weather and endure during the lifetime of the PV panel.

[59] NSG Group, Pilkington group limited, *Solar glass for solar panels*, 2013, retrieved 14 May 2014, <http://www.pilkington.com/products/bp/bybenefit/solarenergy/home.htm>

[60] Madico, *Quality and the Environment*, 2014, retrieved 14 May 2014, <http://www.madico.com/about/manufacturing/quality/>

[61] Vindico, *PHOTOVOLTAIC GLASS STUDY*, retrieved 14 May 2014, <http://www.vindico.info/PDF/PP%20Vindico%20PV+(v5).pdf>

[62] Bunea, G., et.al., *Sunpower, Performance and reliability of modules with anti-reflective coated glass*, 2010, p. 10

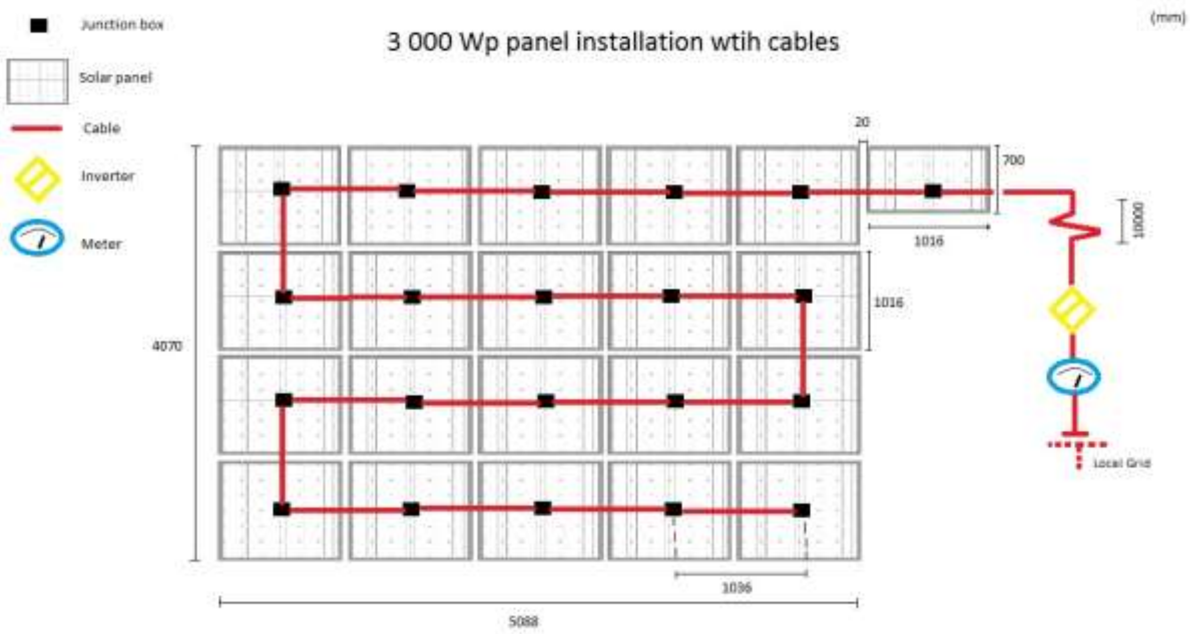

Figure 4: A possible overlay of the PV system mounted on a slanted roof. The image does not represent the electronic schematics and two cable lines to all components as it should be.

2 Goal and Scope

The following sections in this chapter present the actual definitions for this study, unlike section 1.6 where only the methodology was presented.

2.1 Goal

The goal of this study is to determine the environmental impact of a PV system, consisting of solar panels of the model DL 145, and to determine the energy payback time. The reason for conducting this LCA is to bring awareness and knowledge to the company Gaia Solar, a producer of PV panels, of which stages along the cradle to grave chain of the studied system has significant environmental impact and to serve as basis for strategic planning for lowering the environmental impact by making processes more effective or/and to search for alternative suppliers and processes. The study will also serve as information to the interested customers but the LCA is not meant to be public.

The study is performed in accordance with International Energy Agency (IEA) Photovoltaic Power System Programe (PVPS), Task 12, Subtask 20, and will thus be comparable to other LCA with the same methodology, giving awareness to Gaia Solar how their system preforms compared to others.

This study is also elaborated according to ISO 14 040 and ISO 14 044 as far as possible.

2.2 Scope

The scope section consisted of several different sections which are presented below.

2.2.1 Description of the system

The studied PV system is defined as 3 000 Wp (watt peak) peak power, consisting of monocrystalline panels with panel efficiency of 14,20 % and system efficiency of 13,28%, installed on a slanted roof in Copenhagen, Denmark and is connected to the grid during 30 years. Additional results will be included for a lifetime scenario of 40 years. There will also be comparisons with thinner solar cells. The span of the whole system is from cradle to grave.

The reason for including 40 years lifetime in the final presentations is due to the estimated lifetime of the DL 145 solar panel by Gaia Solar. The lifetime of the PV system is stated to be 30-40 years. It is important to include such results even though they are not in compliance with IEA PVPS, Task 12 standards.

The PV system is assumed to be installed on a single floor house within 50 km from Gaia Solar in Copenhagen, Denmark. This is of importance for the cable length and the irradiation used in this study. The irradiation at the location of the house should correspond to irradiation obtained at Gaia

Solar in order to be representative. Solar maps of Denmark[63] shows the irradiation variation throughout the country and is the basis for the assumed distance.

This LCA study will use Ecoinvent data as a foundation for the production of the parts and material included in the studied PV system. Additional data from IEA PVPS Task 12 is used for the assembly and testing of the PV panels and recycling data is obtained from a LCA of PV panel recycling compavy. The properties of the solar panel will be customized, compared to Ecoinvent panels, since the panels, DL 145, used in this study, differ somewhat from ordinary standard metal framed solar panels. Ecoinvent data will be adjusted in order to represent the real case scenario. This involves, extrapolation of data in order to represent a 3 000 Wp PV system as close as possible to the real systems installed by Gaia Solar.

2.2.2 Degradation of the system

Solar panels are not eternal, and when exposed to the elements for long periods of time they perform more and more poorly and resulting in lower energy output with time. There are many factors involved in the degradation such as temperature differences and exposure to harsh weather[64] of any kind, which affect many of the components.

Many reports are published on the degradation ratio of different kind of solar panels and for the monocrystalline solar panels in this study a degradation factor of 0,5% per year is assumed according to the producers Gaia Solar. This value is general for monocrystalline solar panels and confirmed by NERL[65] in their report *Photovoltaic Degradation Rates – An Analytical Review.* This is also a standard value used when actual degradation values are absent[66].

2.2.3 Performance ratio (PR)

The performance ratio determines the percentage of real converted solar energy from the theoretically possible under standard testing conditions[67]. Logically an installed solar panel does not operate in standard testing conditions like in the laboratory and will thus perform differently. PR is affected by many factors such as temperature of the PV module, conduction losses, efficiency factor of the PV module, the measurement gage and more. Below is the formula for calculation of the PR if no official PR value id available.

$$PR = \frac{actual\ reading\ of\ plant\ output\ in\ kWh}{calculated\ nominal\ plant\ output\ in\ kWh} \tag{1}$$

[63] European commission, *Global irradiation and solar electricity potential, Denmark*, retrieved 14 May 2014, http://re.jrc.ec.europa.eu/pvgis/cmaps/eu_cmsaf_opt/G_opt_DK.pdf
[64] Energy informative, *The real lifespan of a solar system*, 2014, retrieved 14 May 2014, <http://energyinformative.org/lifespan-solar-panels/>
[65] http://www.nrel.gov/docs/fy12osti/51664.pdf
[66] Fthenakis, V. et. al., op.cit., p. 4
[67] SMA, *Performance ration – quality factor for PV plant,* 2010, retrieved 14 May 2014, <http://files.sma.de/dl/7680/Perfratio-UEN100810.pdf>

Measured data for the output was supplied by Gaia Solar, corresponding to 925 kWh/Wp and a site specific irradiation data[68] of 1150 kWh result in a performance ratio of 80,4 %. This is for a whole PV system including losses in the inverter for instance. A PV system will have losses in the inverter (DC/AC) and a good inverter with efficiency above 90%, as the case in this study (93,5%), will result in a total PR of 0,8 for the PV system[69,70]. Thus an overall PR of 80% is used in this study.

2.2.4 Ecoinvent methodology

Available data on the Ecoinvent database allows for a vast choice between processes and sub processes. Data for a whole PV system is available if needed but since that PV system differs from the one used in this LCA, there has to be an alternative choice to just using that data. Otherwise parts and processes that are not included in this LCA will be presented anyway, neglecting the measures and parts that differ.

Even though the Ecoinvent data for a whole PV system is not relevant for this study, it can be used for the processes that make up the system. For instance the glass production, anti-reflective coating, insulator and monocrystalline solar cells are all relevant for this LCA and by choosing only the relevant processes combined with additional own data, a new scenario will be obtained reflecting the conditions for Gaia Solar better.

The assembly and testing of the PV modules are both conducted at Gaia Solar. LCA data is collected for all steps presented in figure 5 below in order to achieve the goal and scope of the study.

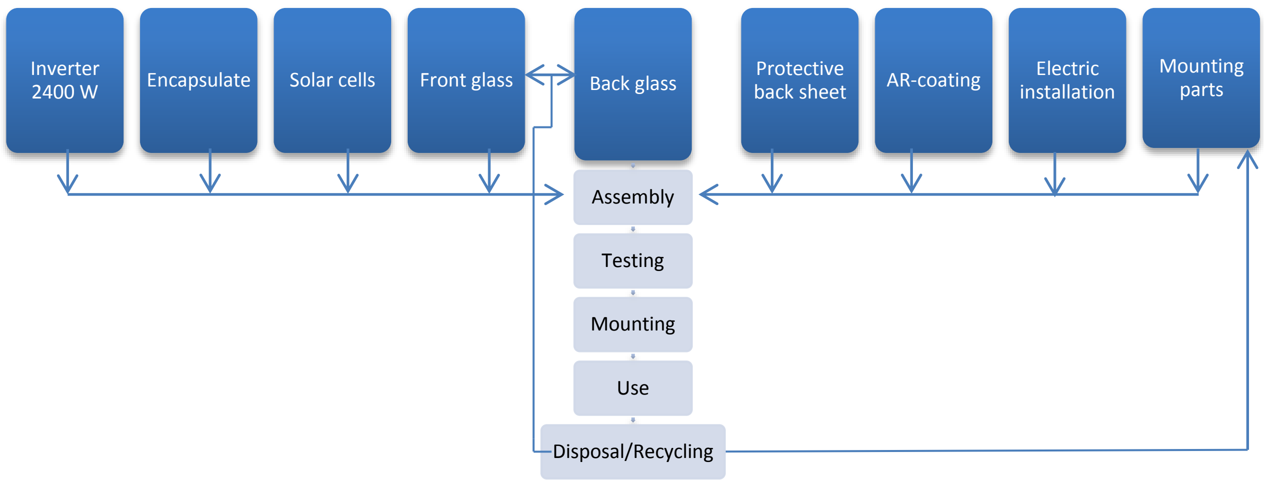

Figure 5: Principle flowchart showing the included processes in this LCA.

[68] European commission, op.cit.,
[69] Renewable energy world, *BOS Series: Your new solar array.* 2012, retrieved 14 May 2014, <http://www.renewableenergyworld.com/rea/news/article/2012/04/your-new-solar-array-actual-performance-may-vary>
[70] SMA, op.cit., p. 2

2.2.5 System boundaries

Below is a simplified flowchart of the process. Note that the chain in figure 6, from extraction of resources to deposition/waste, is valid for all resources such as iron, copper, etc., and thus for all sub-products. It is also valid for all impact categories, trough emissions from every stage.

The final boundary is at the connection point to the local grid. According to IEA PVPS Task 12, the final boundary should not be any other and must include meters and a full electric system. With that said, the PV system boundary cannot end at, for instance, the solar panels.

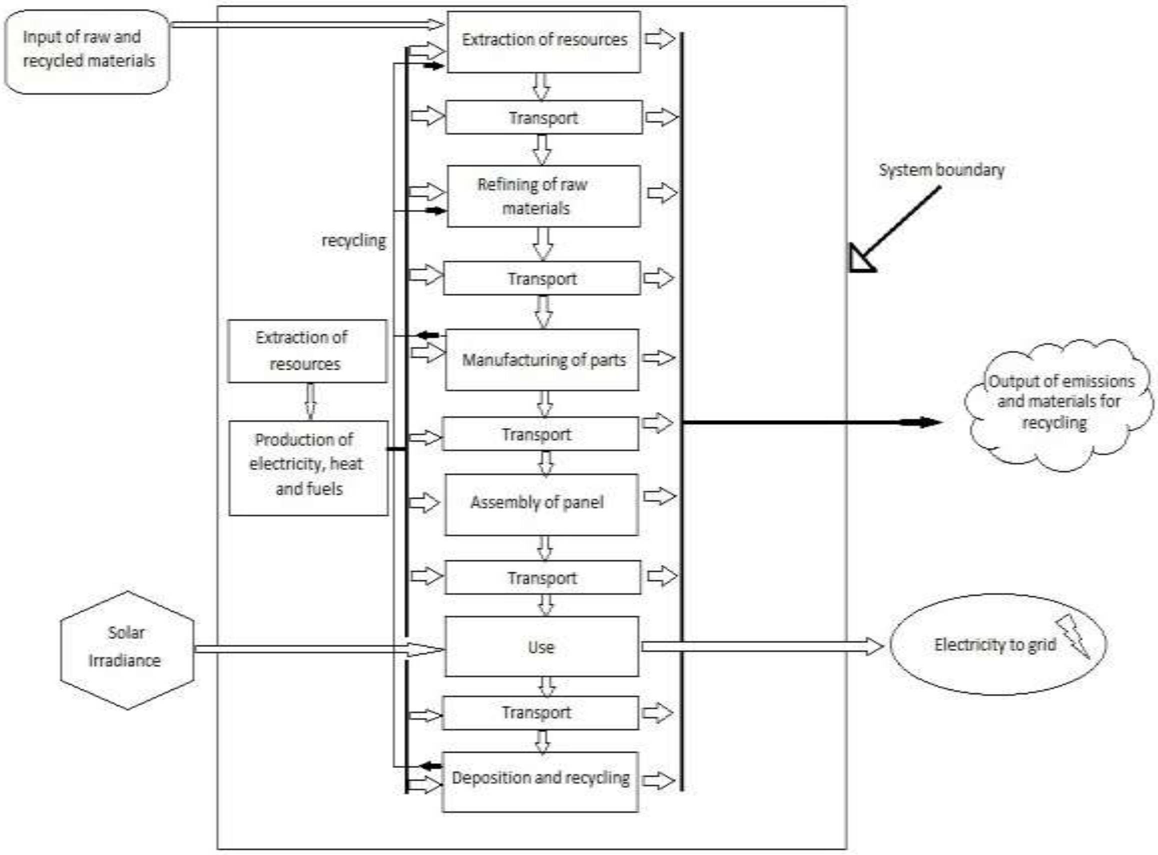

Figure 6: Simplified flowchart of the studied system with included energy-, material- and emission flow

2.2.5.1 PV system parameters

Below are presented few basic parameters used in the calculations of this study. Parameters were obtained from Gaia Solar documents, IEA PVPS Task 12 directives and own calculations based on provided parameters.

Table 2: PV system parameters.

Installed effect	3 000 Wp
Panel capacity	145 Wp
Panels amount	20,70
Panel efficiency	14,20%
Cells per panel	36
Cells, amount	745,20
Inverter efficiency	93,5%
PV system efficiency	13,28%
Specific annual yield	925 Wh/Wp
Degradation rate	0,5%/year
Lifetime expectancy	30 years

2.2.5.2 Technological coverage

Conclusion, based on PV evolution charts, show that the PV technology is old (>37 years since the first solar panel[71]) but small efficiency advances are made regularly. A solar cell diagram from NREL (National Renewable Energy Laboratory) shows that the monocrystalline solar cells have not developed in efficiency more than 4% since 1995[72]. It is a reasonable conclusion that the monocrystalline solar cells technology, as it is today, will not increase noticeably in the near future. Other solar technologies may on the other hand do so.

On the other hand, new factories are constructed to supply the demand for solar cells and they may be more efficient than the one in Ecoinvent from 2005. Production processes and more efficient plants are with highest certainty available today, compared to 2005, but unfortunately such data is not available as a basis for this study. The data will thus be exaggerated compared to a brand new plant and improved processes but to what degree is uncertain.

Additional information, based on scientific studies, will be included anyway in a comparison diagram in the result section. Comparison data on the thickness of the solar cells was available and thus own calculations were applied to Ecoinvent data in order to simulate the new, actual thickness, of the solar cells. All results, except the comparison chart, will still be based on Ecoinvent data of solar cells, since it is based on actual measurement and impact results, but the comparison chart will be more representative for the real case scenario. This will be discussed further on in the study.

2.2.5.3 Geographical coverage

The Ecoinvent data is gathered from different parts of the world where the majority is from European sites. The study is made according to Danish conditions (local) regarding energy use for assembly and solar irradiance which is in compliance with the IEA PVPS Task 12. All inputs and outputs to and from the system are included despite different location. There are thus no geographical boundaries set.

[71] exploringgreentechnology.com, *History of solar energy*, 2014, retrieved 14 May 2014, <http://exploringgreentechnology.com/solar-energy/history-of-solar-energy/>
[72] SolarContact, *How to compare solar panels*, 2014, retrieved 14 May 2014, <http://www.solarcontact.com/solar-panels/types/solar-panel-efficiency>

2.2.5.4 Time coverage

Data is gathered mostly from the Ecoinvent data base. The age of this data ranges from 2002 to 2008 where the majority of the data is from 2005. See appendix 4 for further information regarding inventory date.

2.2.5.5 Upstream processes

Upstream data includes processes on a global scale and thus different energy mixes are included in the inventory[73]. Upstream data includes:

- Extraction of materials
- Refining of material
- Production of components
- Assembly of PV panels
- Transportation for and between all mentioned stages

2.2.5.6 Downstream processes

All processes after the PV system have reached its lifetime end and thus out of service.

- Deposition/recycling
- Transportation

2.2.5.7 User phase

All the processes between installation and disassembling.

- Service and parts exchange
- Electricity provided to the household or/and grid

2.2.5.8 Excluded phases

- Construction of buildings and machinery used for making the PV system
- Deviation from normal operation and extraordinary events

[73] Jungbluth, N., et.al., op.cit., p. ii

2.3 Function unit (FU)

The function unit is 1 kWh net of electrical energy delivered to the grid, generated from solar power by the PV system.

2.4 Reference flow

The reference flow is a PV system of 3 000 Wp, from cradle to grave, containing all parts of a functional PV system and panels of model DL 145 with an effect of 145Wp.

PV system studies are encouraged to use the same reference flow as IEA PVPS Task 12 states. Even the Ecoinvent data is assumed to have a reference system of 3 000 Wp. The fact that PV systems in Denmark today have to be under 1 000 Wp, due to legislations, does not conflict with the studies 3 000 Wp system since the data and size are relative.

2.5 Secondary function

Aesthetics is one of the niches of the company Gaia Solar, resulting in outstanding design features of solar panels. A secondary function of this LCA might thus be to evaluate the aesthetic function gained by installing this PV system but sense such assumptions and conclusions are subjective to their nature, it is excluded as a secondary function. There is thus no secondary function.

2.6 Allocation

Because Ecoinvent data is used for whole separate processes such as invertor, low iron glass, wafer sawing etc. the necessary allocations are already conducted in the sub processes. This is of great importance since the production of one stage of solar cells is formation of MG-silicone (Metallurgical Grade silicone). The majority this compound is not used for solar grade silicon but instead for other processes such as aluminum compounds (50% of total MG-silicone), silicones/plastics (40% of the total MG-silicone) and only 4% for the next step in the solar cell manufacturing[74].

No further allocation is necessary during the assembly stage at Gaia Solar since the only product is solar panels.

Allocations are made on the recycling of the glass and aluminum roof installation. This is described further on in the study and calculations are presented in Appendix 1.

[74] Jungbluth, N., et.al., op.cit., p. 16

2.7 Impact categories

Resources

- Cumulative energy demand (kWh)
- Primary energy consumption, renewables (kWh)
- Primary energy consumption, non-renewables (kWh)
- Materials resource (kg)
- Land (m^2a)
- Water (m^3)

Human effect

- Human toxicity, 100 years (kg 1,4-DCB-equivalents)
- Ionizing radiation (DALYs)

Environmental impact

- Global Warming Potential, 100 years (GWP-100, kg CO_2-equivalents)
- Acidification potential (AP, kg SO_2 -equivalents)
- Eutrophication potential (EP, kg NO_x - equivalents)
- Ozone depletion potential, 10 years (ODP-10, kg CFC-11-equivalents)

Energy payback time

- Energy payback time (EPBT), in years

The table below represents the geographical range of the effect from different impact categories.

Table 3: Effect of impact categories on geographical regions. Eutrophication is regarded as regional amongst some sources (Rydh, C.J., et.al.) and as local amongst others (EPA). Distance are according to Rydh, C.J., et.al.. Sources: Rydh, C.J., et.al., EPA.

Global Impact diameter > 1000 km	**Regional Impact** 1000 km > diameter > 100 km	**Local Impact** 100 km > diameter
- Cumulative energy demand - Material resources - Global Warming Potential - Ozone Depletion Potential	- Acidification - Eutrophication	- Human toxicity - Ionizing radiation - Land resources - Water resources

2.8 Characterization methodology for LCA

Raw inventory data comes in tremendous sizes, including all different small process flows, and therefore needs to be characterized (sorted out) in different impact categories in order to be presented in more understandable, aggregated, categories such as acidification potential, human toxicity etc. As mentioned earlier, different substances impact on different categories to different extents. Ecoinvent presents data processed by many different LCA characterization tools, which treat the inventory data different, based on the methodology of the LCA tools[75]. A few of these LCA characterization tools that are used in this study are described in the next section.

Often, one impact category is presented in several “time periods” because substances have varying lifetime in different environments. For instance, if substance A contributes to global warming and has a lifetime of 50 years it would be unwise and not representative if the category Global Warming Potential 500 years is chosen, since the substance would be absent. A suitable representation for that substance would instead be Global Warming Potential 20 years. The same logic is valid for rest of the impact categories.

In order to be as representative as possible, the time periods of the categories with the highest result are included in this study. One exception is Global Warming Potential which is 100 years and not the lowest parameter, 20 years. This is due to directions from IEA PVPS Task 12 which state that global warming potential should be 100 years.

2.8.1 EDIP (Environmental Design of Industrial Products)

EDIP is a LCA tool determining three impact categories: environmental impact, resource consumption and working environment. The method was developed in Denmark by the Danish Technical University, Environmental Protection Agency of Denmark, Confederation of Danish Industry and 5 industrial companies[76].

This study includes one impact category from the EDIP since it was the best represented in highest detail in Ecoinvent database. The impact category is resource consumption.

EDIP treats the resources as a quota of yearly extracted resources compared to the approximated global resource reserve[77].

Resources presented by EDIP include materials for production such as aluminum, zinc, copper etc. but also energy resources such as coal, oil and natural gas. They are only presented as extracted resources and not presented as energy. Energy is presented from another LCA tool namely cumulative energy demand.

2.8.2 CED (Cumulative Energy Demand)

CED takes into account the total primary energy input required for producing a product[78]. The impact category; Cumulative Energy Demand and sub impact categories: Primary energy consumption, renewables and Primary energy consumption, non-renewables presented in this study, originate from Ecoinvent CED data.

[75] Rydh, C.J., et.al., p. 119
[76] Rydh, C.J., et.al., p. 126
[77] ibid.
[78] Röhrlich et al., *LCA Case Studies, A method to calculate the cumulative energy demand (CED) of lignite extraction*, 2000, p. 369-370

2.8.3 Selected LCI results, additional

Water use is best represented in Ecoinvent by the category: selected LCI results additional.

Selected LCI results, additional is a sub group to selected LCI results. They describe summarized substance emission to different sub-compartments[79] and water is one such substance.

The impact category "Water", presented in this study originates from Ecoinvent, Selected LCI results, additional.

2.8.4 CML 2001

CML 2001 (Center for Environmental Science of Leiden University) is a characterization and normalization tool developed by the Environmental Science University in Leiden in Netherlands[80]. It is widely used in LCA studies and includes many impact categories for over 1 700 flows[81].

This LCA uses CLM 2001 for several impact categories such as GWP 100 (Global Warming Potential, 100 years), AP (Acidification potential, average European), EP (Eutrophication Potential, average European), ODP 10 (Ozone Depletion Potential 10 years), ionizing radiation and HT 100 (Human Toxicity, 100 years).

2.9 Balance of system (BOS)

When conducting LCA on PV systems, IEA PVPS together with Ecoinvent report no. XII state that a balance of system should be included and presented.

Balance of system includes parts of the PV system that are not included in the solar panel. Mounting frame, electric installation (all components such as cables, junction boxes, meters and lightning protection) and inverter fall under the title BOS[82]. BOS can be seen as a gathering category for mentioned parts just as a PV module can be seen the same. PV modules themselves include many parts such as solar cells, encapsulates etc. Different cases of PV systems result in different BOS[83]. For instance a ground mounted PV system and a building integrated PV system (BIPV) require different amount of the mentioned component in BOS. BOS for large scale PV systems include even facilities, concrete and grid connectors[84].

All components for BOS in this LCA are presented separately, more detailed, but will be denoted with BOS in the results.

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[79] EarthShift, *Selected LCI results*, 2012, retrieved 14 May 2014, <http://www.earthshift.com/software/simapro/selectedlci>

[80] EarthShift, *CML 2001*, 2012, retrieved 14 May 2014, <http://www.earthshift.com/software/simapro/clm2001>

[81] GaBi Software, *CML 2001*, 2012, retrieved 14 May 2014, <http://database-documentation.gabi-software.com/support/gabi/gabi-lcia-documentation/cml-2001/>

[82] Fthenakis, V. et. al., IEA – PVPS – Task 12, *Life cycle inventories and life cycle assessment for photovoltaic systems*, p. 17

[83] Jungbluth, N., et.al., op.cit., p. 89

[84] Fthenakis, V. et. al., 17

2.10 Data quality

The majority of the data is from Ecoinvent, thoroughly measured and transparent. Newer data is also used from the report from IEA PVPS Task 12, *Life cycle inventories and life cycle assessment for photovoltaic systems*. The majority of the data originates from 2006-2007 although some cases are newer and older. See metadata in Appendix 4 for further information. The data and additional information will be presented in the coming sections.

Overall the data is to be considered as reliable based on professional data collection during several years at different sites. For further information see Appendix 4.

Recycling data is obtained from the recycling company LCA[85] from 2012.

2.11 Limitations and assumptions

The main limitation and uncertainty of this study is the lack of LCA data for the real parts, provided to Gaia Solar by suppliers. Instead measured data from other corresponding processes from Ecoinvent is used. The age of the data and data obtained at different companies in Ecoinvent is not 100% representative to the real components produced in different, more modern industries. But there is little to no possibility to include actual data due to lack of LCA's. Therefore only the available data from Ecoinvent will be presented despite the limitations. Additional information on the industrial production efficiency evolution and material reduction obtained from trustworthy PV studies will be presented as well and compared to the results obtained from Ecoinvent. One important process that has been drastically improved is the reduction of the solar cell thickness, leading to more solar cells produced per raw monocrystalline feedstock and thus lowering the environmental impacts of the solar cells.

There are limitations regarding the recycling of the used PV panels because of lack of data and information. Available LCA on recycling enabled the inclusion of some PV system parts, such as the glass and aluminum roof installation. The other components are not assumed to be recycled and are instead deposited. This will be discussed further on in the study. Some deposition and recycling of the production of sub-processes is on the other hand regarded in every step, to some extent. Some raw materials are treated, disposed and/or recycled, but not the whole sub-products. Therefore the use of recycling data for the big parts, glass and aluminum roof installation, is convenient in order to present them as recycled. Further more detailed information can be found in the unit process raw data in Appendix 3.

Furthermore, performance of the system is assumed to be reduced by 0,5%/year due to degradation.

Two inverters are assumed to be used during the lifetime of the PV system while other the parts are assumed to endure the whole lifetime.

The irradiation is assumed to be equal each year of the PV system lifespan meaning that the PV system should output the same amount electricity each year if no degradation occurs.

The Danish electricity mix is assumed to be as it is today, for the duration of the PV system.

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[85] Fraunhofer IBP, *Life cycle assessment (LCA) screening of the Maltha recycling process for PV-modules*, 2012, retrieved 14 May 2014, http://www.pvcycle.org.uk/wp-content/uploads/Exec-Summary-LCA-Screening-of-a-Recycling-process-of-silicon-based-PV-modules-2012-07.pdf

The production of protective back sheet is assumed to the stage where a bulk of finished product is obtained. The real PBS on the other hand has to be formed into thin films, a process which is not included in the study due to lack of data. This excluded final process is somewhat irrelevant due to 2 reasons. First, the PBS plays a very small role in the entire PV system, see Appendix, transportation section and results for data on impact categories and mass of the PBS. Second, the process of acquiring bulk of the raw materials probably overweighs the single process of sheet production form bulk material.

A few more assumptions are described and discussed further on in this study.

3 Life cycle inventory (LCI)

All upstream steps for all parts included in the PV system are accounted for. Transports between every sub-process/refinement are included, material and energy supply as well as all emissions and recycling and deposition materials. Additional transportation to Gaia Solar and to the location for the PV system is also presented.

The inventory will only present the unit process raw data from Ecoinvent, meaning the main inputs and outputs for a product. The real inventory data will not be presented due its tremendous size of 45 pages per sub-unit. Although the data will not be presented, its effects will be presented indirectly after being categorization into the impact categories and the LCIA, since characterization structures all flows into a few impact categories.

3.1 Parts for PV system

3.1.1 Solar cells

There are several pathways when producing a complete ready to use solar cell. The processes are intended to purify silicon from the processed quarts sand in order to obtain as high degree of purity as possible. It starts with the treating the sand to metallurgical grade silicon (MG-silicon)[86]. Here is where the processes split and the processes begin to differ.

The obtained MG-silicon can thereafter be purified yet again if intended to be used as electronic grade silicone (EG silicone) the next step, or the MG silicone can be used directly to manufacture solar grade silicone (SoG silicon) intended only for production of solar cells[87]. The EG silicone process only allocates a small fraction of the material for solar cell production, whiles the majority is used for other products, as mentioned earlier in the study.

[86] Fthenakis, V. et. al., p. 4
[87] Jungbluth, N., et.al., op.cit., p. 16.

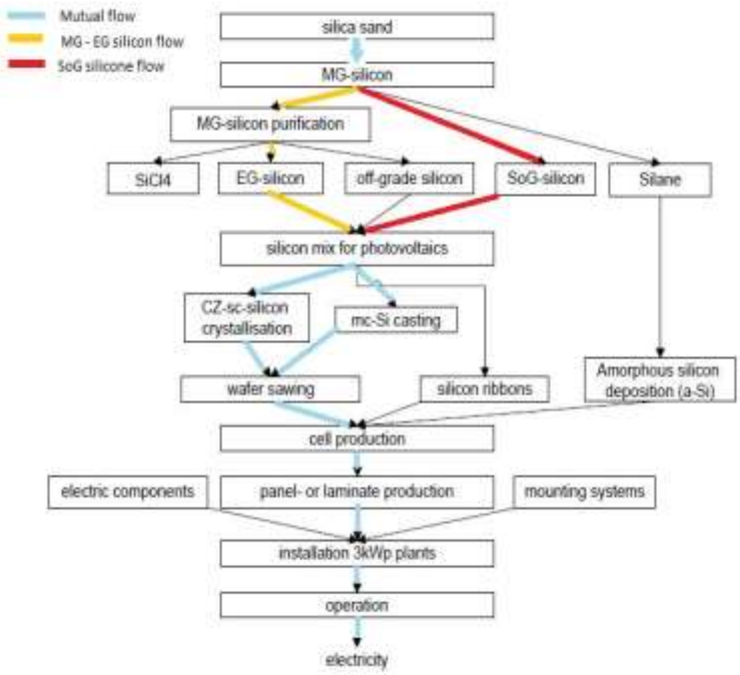

Figure 7: Process chart for manufacturing of poly- and monocrystalline solar cells. Modified from source: Jungbluth, N., et.al., p. 14

Both steps however can result in a polycrystalline and monocrystalline solar cells but by different pathways. SoG silicon is a newer method since 2005 and requires less electricity for production of silicon ready for solar cells[88]. Figure 8 below presents the electricity demand from only one step of the whole solar cell process line. While the modified Siemens process requires only one step to produce solar ready silicon, the other pathway requires two for the same purpose. See figure 7 for clarification.

Solar cells produced from the EG-silicon pathway are much purer than those from the SoG-silicon, since there are originally intended to be used in other products which require that high purity grade of silicon[89]. Large demand of solar cells has led to the development of processes intended for solar cell silicon only, like the SoG-silicon process. This process in much cheaper in relation to the output of electricity, due to the impurity difference between the two processes.

[88] Jungbluth, N., et.al., op.cit., p. 26
[89] ibid.

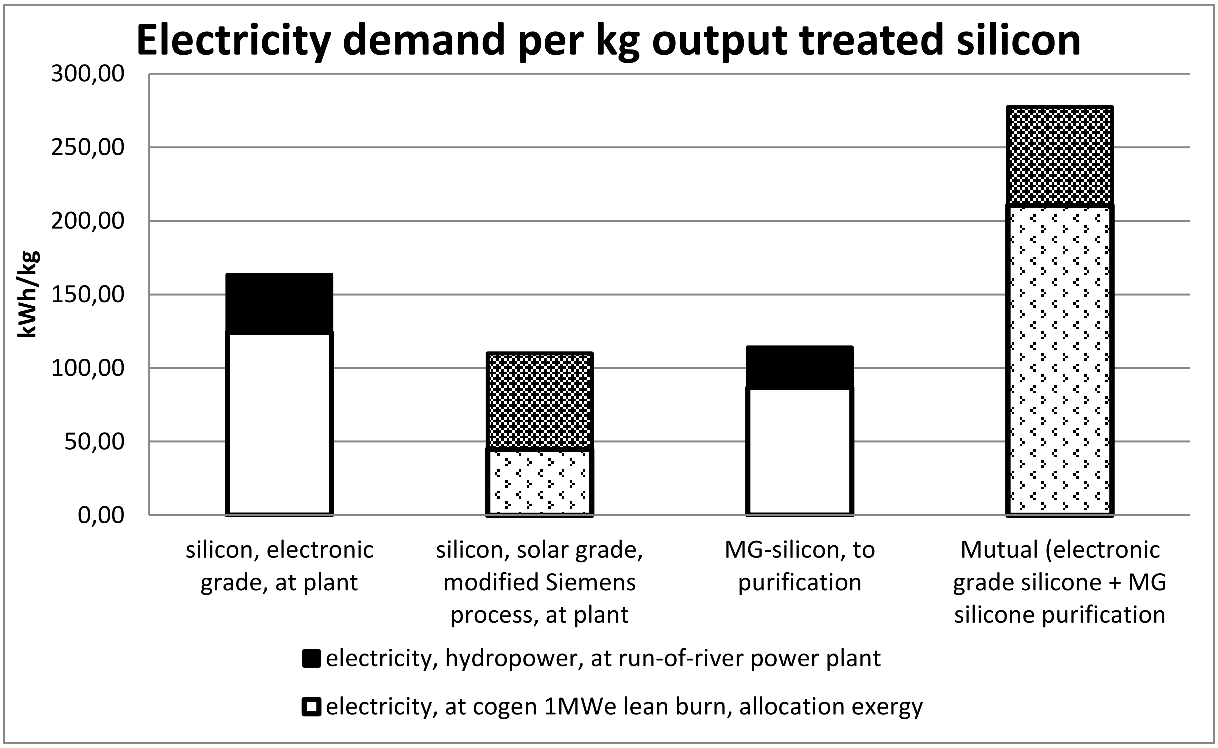

Figure 8: Electricity required for the purification of MG-silicone to silicon ready solar cells, by the two different methods. MG-silicon purification and electronic grade silicon are fused into once mutual column since they correspond to the modefied siemens process as seen in Figure 7. In the end, the comparable columns are the patterned ones. Data is gathered from Ecoinvent. Note that the unit is in kg and not in the total weight of the requiered solar cells for 3 000 Wp PV system. The diagram only illustrates the relationship between the processes regardless of the unit.

This study follows the SoG-silicon (modified Siemens process) only, and therefore there will be no further description of the MG-silicon purification and EG-silicon production.

The following process, after SoG silicon, is the silicon production mix which is used for both poly- and monocrystalline cells. The purity is raised above 98% before the material is ready for the next step which is formation of mono crystalline feedstock by a process called “Czochralski process” (CZ process)[90]. This step is specific for production of monocrystalline solar cells only. After the Czochralski process, the silicon feedstock is sawn into wafers that are treated before proceeding to the solar cell production step. All the treatment steps in during different stages can be found in the metadata in Appendix 4. After the solar cells are produced, different metallization pastes are applied on the sell such as metallization paste on the front of the cell, on the back of the cell and an aluminum plate on the back of the cell[91]. After this metallization process the cells are ready for ready for use and thus the production step for solar cells is finished.

Below is a flowchart of the production cycle of solar cells. The mass and energy flow are presented as well and correspond to a 3 000 Wp PV system.

[90] CZ-silicon, Metadata, Appendix 4
[91] Jungbluth, N., et.al., op.cit., p. 63

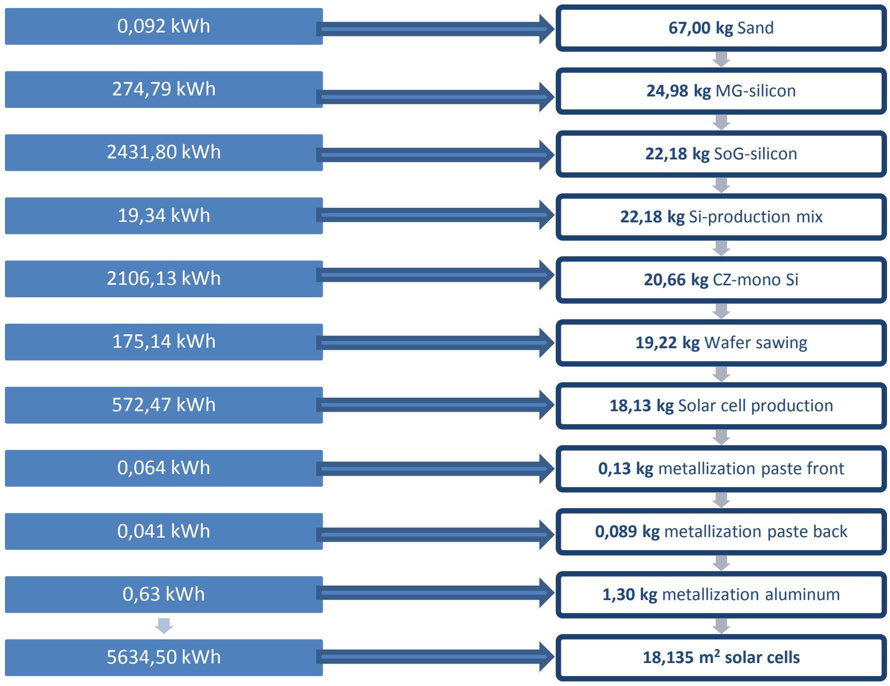

Figure 9: Production chain for ready to use solar cells. The mass corresponds to solar cells in 3 000 Wp PV system. The primary energy is presented as well.

Due to the tremendous amount of processes and their complexity, the production step of monocrystalline solar cells will not be described in depth in this study. Readers with higher desire of this process are referred to other specific literature such as Part XII photovoltaic (*Niels Jungbluth, Matthias Stucki, Rolf Frischknecht, ESU-service Ltd., Ulster, http://www.esu-services.ch/fileadmin/download/06_XII_Photovoltaic-v2.2plus.pdf*).

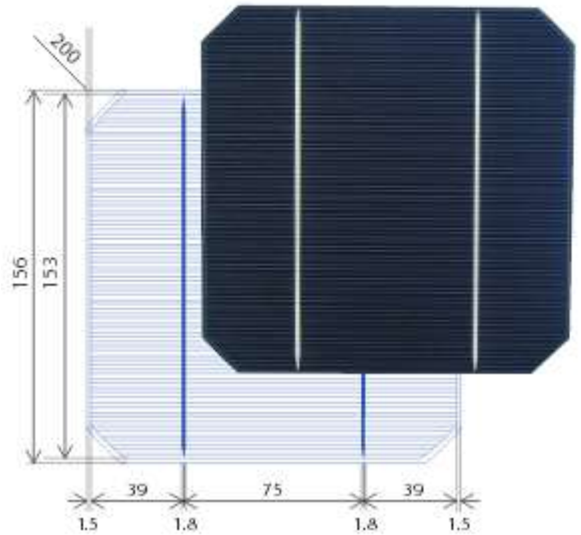

Figure 10: A monocrystalline solar sell from Sunrise including dimensions. Source: Gaia Solar.

3.1.2 Inverters

The inverter in this study weighs 18,5 kg and is produced in Germany (DE) by the company Mastervolt. The Inverter has an nominal power of 2 500 W and nominal efficiency factor of 93,5%[92]. The real inverters used by Gaia solar are on the other hand produced locally in Denmark by Danfoss and are near the same weight and nominal efficiency as the Ecoinvent inverter. There is thus no essential difference in resource use for the inverter construction. The Danfoss inverter[93] weighs 19-21 kg and has a maximum efficiency of 97% but presumably lower standard operation efficiency. The impact from inverter production will therefore be representative for German conditions and energy mix but the transportation will be between the real inverter factory and Gaia Solar.

Due to the difference between the lifetime of the inverter and the solar panel, 2 inverters are included to fulfill the lifetime expectancy of the solar panel. The PV panel has a life expectancy of 30 years and the inverter only 15 years[94]. The total data for the inverters are thus double that of one inverter.

An inverter contains many different parts and thus consists of several upstream processes. Below is a table containing data for the inverter used in Ecoinvent.

Table 4: Inverter parameters.

Component	Unit	Inverter, 2500W, at plant	
		Value	Remarks
Aluminium	kg	1.4	casing
Polycarbonate	kg	-	casing
ABS	kg	-	casing
Poly Ethylene	kg	-	
PVC	kg	0.01	in cable
SAN (Styrene acrylonitrile)	kg	0.01	in cable
copper	kg	0.01	in cable
Steel	kg	9.8	screws and clamps
Printed Circuit Board	cm^2	2246	without components
connector	kg	0.237	
transformers, wire-wound	kg	5.500	
coils	kg	0.351	
IC's	kg	0.028	
transistor	kg	0.038	
transistor diode	kg	0.047	
capacitor, film	kg	0.341	
capacitor, electrolytic	kg	0.256	
capacitor, CMC	kg	0.023	
resistors	kg	0.005	
polyamide injection moulded	kg		
polyester	kg		
Polyethylene, HD	kg		
Paint	kg		
Transformer oil	kg		
Total	kg	18.5	

[92] Jungbluth, N., et.al., op.cit., p. 103
[93] Danfoss DLX, *The Danfoss DLX PV inverter series*, 2012, retrieved 14 May 2014, <http://solarsysteme.baywa-re.com/media/filer_public/d3/1c/d31cc494-e22c-4471-93c7-3331acc6cc7f/dksipfp203a202_dlx_factsheet_web.pdf>
[94] Fthenakis, V. et. al., IEA – PVPS – Task 12, *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 2011, p. 2

There are no recalculations made in the inverter data except accounting for two whole inverters.

See metadata in Appendix 4 for further detailed information on the inverter.

3.1.3 Electric installation

The electric installation used for this LCA consists of all cables, cable clamps, junction boxes, electronic meter but not the inverter. The available Ecoinvent data is somewhat old and not really accurate. For instance, the data includes a fuse box, domestic electricity meter and grid electricity meter but as mentioned earlier there now exist smart inverters which supply the user with that information rendering the local meters useless. Of course the new smart inverter can be seen as a fusion of the local meter and the basic inverter since the new inverter contains the circuits and electronics that the meter did to some degree. Fusion of the meter and the inverter is instead assumed, leading to the same result but presented at different process. Instead of being presented for the inverter data it will be presented in the electric installation section as separate meters.

Another uncertainty is the cabling. According to Jungbluth, N., et.al., the cabling should be between 200 and 400 meter and the cable size is 2,5mm^2 copper wire. This is not valid for the cable amount and dimensions of the present electric system used by Gaia Solar and will therefore be taken into account by performing a percentage recalculation. Ecoinvent data is found in table 4.

Gaia Solar uses two, 1 m cables for every panel installed but of 4,0 mm^2 dimension and since a 3 000 Wp system includes 20,7 panels this results in 41,4 m. Another 20 meter cabling is assumed to connect the panels to the inverter and to the meters. This results in a total of 61,4 m cabling. The Ecoinvent data represents a 245m x 2,5mm^2 cabling. Recalculation follows, where parameters denoted with 1 are the ones used in this LCA and parameters denoted with 2 are Ecoinvent data.

$$\frac{L_1 * A_1}{m_1} = \frac{L_2 * A_2}{m_2}\ ;\ \ m_2 = \frac{L_2 * A_2 * m_1}{L_1 * A_1} \tag{2}$$

$$\frac{61{,}4\ m * 4{,}0\ mm^2}{m_1\ kg} = \frac{245\ m * 2{,}5\ mm^2}{4{,}66\ kg\ Cu};\ m_1 = 1{,}96\ kg\ Cu$$

Bearing in mind that the cabling is much less in this LCA compared to Ecoinvent data, this results in less copper and other materials necessary to cable production. Percentage calculation follows:

$$x = \frac{m_1}{m_2} \tag{3}$$

$$x = \frac{1{,}96\ kg}{4{,}66\ kg} = 0{,}42;\quad x = 42\%$$

The reason why percentage calculation is based upon copper is that it contributes to highest life cycle impacts assessment according to Ecoinvent database search of copper compared to PVC. Therefore the percentage of remaining materials necessary to produce a cable will be lowered with the same magnitude as copper.

$$total\ mass\ cable_2 = \sum all\ components_2 = 12{,}61\ kg$$

$$total\ mass\ cable_1 = \sum all\ components_2 * 0{,}42 = 5{,}29\ kg$$

Having calculated the total cable mass for the case of this LCA, there now needs to be yet another percentage calculation preformed, comparing the new mass to the whole electric installation which will thus result in a final value. Calculation to determine how much the new electric system relates to the system from Ecoinvent follows:

$$total\ mass\ of\ ES_1 = \frac{(total\ mass\ of\ EI\ _2 - (total\ mass\ cable_2 - totla\ mass\ cable_1))}{total\ mass\ of\ ES_2} \quad (4)$$

Where,

ES_1 = Electric $System_1$

ES_2 = Electric $System_2$

EI_2 = Electric $Installation_2$

$$total\ mass\ of\ Electric\ System_1 = \frac{(32{,}61 - (12{,}61 - 5{,}29))}{32{,}61} = 0{,}7755 = 77{,}55\%$$

The system assumed in this study is 77,55% of the system presented by Ecoinvent and thus all the results in the LCIA will be recalculated to represent the studied system. The resulting weight of the electric installation is 25,29 kg.

Table 5: Materials and materials masses of Ecoinvent electric system. Source: Ecoinvent XII photovoltaics.

Part of installation	Material	Mass
		kg
Lightning protection PV-plant	copper (28 mm^2 Cu)	2.5
Cabling PV panel area	wire (245 m): copper	4.66
	Radox 125	5.39
	PVC-isolation tube (9 m)	2.13
	cable clip(plastics)	0.32
	cable lug (copper)	0.11
Fuse box	copper	0.31
	steel	0.77
	plastics	1.34
	brass	0.02
	Polycarbonate	0.20
	Polyamide	0.23
	ZnO	0.04
	Epoxy (Lack)	0.002
	Radox 125	0.02
PV panels to inverter	wire (10m): copper	1.82
	Radox 125	2.69
	protection (copper)	0.97
	plastic tape	0.03
	cable lug Noryl (10m)	3.60
	grounding wire (10m): copper (16 mm^2 + 10 mm^2 Cu)	2.3
	Radox 125	0.30
	heat shrink tube (20cm): PE	0.02
	nail dowel: PE	0.16
Inverter to electric meter	grid cable (5m): copper	0.25
	Thermoplastic	0.17
	grounding wire (8m): copper (25 mm^2 Cu)	1.76
	Radox 125	0.32
	switch: copper	0.02
	plastics	0.07
	steel	0.09
Total		32.612

No other calculation will be further performed on the electric system assuming all other remaining parts are representable.

For further unit process raw data, see Appendix 3.

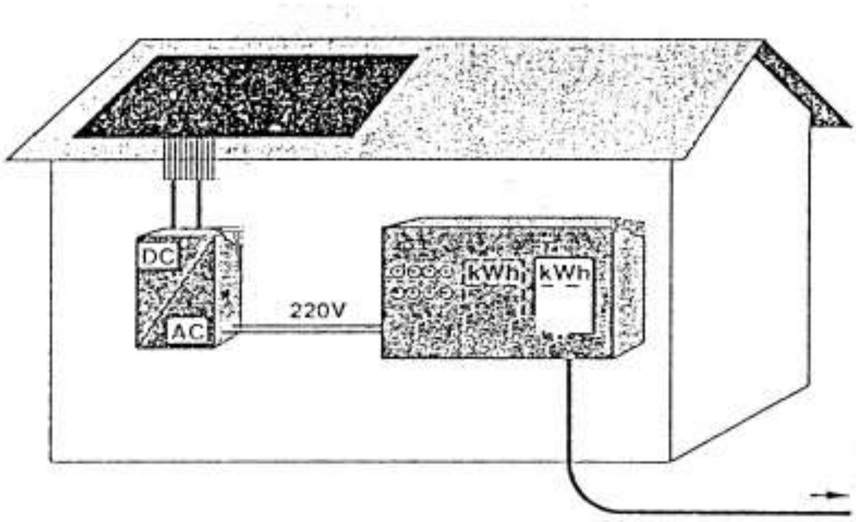

Figure 11: Electric installation components included in Ecoinvent data of the studied PV system. Modified from source: Jungbluth, N., et.al., op.cit., p. 110.

3.1.4 Slanted roof PV structure installation

The slanted roof installation is assumed to differ from the one in Ecoinvent. The structure consists predominantly of aluminum rails but also include iron screws, bolts and fuses and some plastic parts as well[95]. The purpose of the mounting system is to attach the panels to the roof in a secure and safe way. Mounting structures should be robust and endure wind and snow. A gap between the roof and the panels enables wind to pass between and thus cool the PV system which increases the efficiency of the PV system[96].

Slanted roof installation data was latest updated by Ecoinvent in 2008 and is thus newer than many other included parts in this LCA. For more detailed information of the roof installation, see Appendix 4 metadata and Appendix 3 for unit process raw data. The table below presents the resources, and their mass, included in the slanted for the Ecoinvent structure.

Table 6: Material data for the slanted roof installation presented in weight/m2, Source: Ecoinvent report no. 6, part XII.

	Weight (kg/m2)
Aluminum	2,8
Steel	1,5
Rest	0,1
Total weight	4,7

The real structure used by Gaia Solar is slightly different and requires less materials per m^2 to fulfill the same purpose. The table below presents the values for the frame used by Gaia Solar.

[95] Jungbluth, N., et.al., op.cit., p. 91
[96] ibid., p. 90

Table 7: Material data for the actual roof installation measured by Gaia Solar.

	Weight, kg/m^2
Aluminum clamps and bolts	0,6
Aluminum rails	1,6
Total aluminum	2,2 kg/m^2

There is a difference of 0,6 kg/m^2 in the aluminum between the two cases. Since the roof installation data is representative for the Ecoinvent case, a recalculation is required in order to make the real case data representative. A reduction of 21,4 % of the Ecoinvent aluminum content in the roof installation corresponds to the real case scenario. All other parts are assumed to be lowered by the same amount. A total of 78,6% of Ecoinvent data for roof installation is used in this study.

3.1.5 Encapsulate

Gaia Solar uses 2 encapsulate layers in their solar panels. The encapsulate consists mostly of EVA (ethylvinylacetate) but in this study it is assumed to be solely composed of ethylvinylacetate, since Ecoinvent data about encapsulate did not exist but there was data about the production of EVA. There is a difference between the mentioned two, namely the process of producing EVA sheets from the pure compound. Because of the lack of data regarding the production of the sheet from bulk material, it is excluded.

Ecoinvent EVA data was presented in 1 kg of produced EVA and not in 1 m^2 as needed. A combination of EVA parameters from Gaia Solar documentation and the density number of EVA enabled the recalculation from 1 kg to 1 m^2. Parameters about EVA are presented below:

Table 8: EVA parameters.

Density[97]	960 kg/m^3
Area	1,032 m^2
Thickness	0,000460 m
Volume	0,000473 m^2
Sheet weight	0,455 kg
Percentage (actual data/Ecoinvent data)	45,5%
Total panel area	21,367 m^2

All Ecoinvent data for EVA is recalculated to represent 1 m^2 of EVA sheet. In total only 45,5% of Ecoinvent data is considered and used for the impact categories stated in this LCA. Obtained representative data for the EVA is then extrapolated for a 3 000 Wp system, in this case multiplied by 21,367 m^2.

See further unit process raw data in Appendix 3.

[97] Fthenakis, V. et. al., IEA – PVPS – Task 12, *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 2011, p. 32

3.1.6 Back and front glass

The back glass is, as mentioned earlier, a vital component for the stability of the solar panel and an alternative to aluminum frame. The actual back glass is thus not treated or coated like the more advanced front glass since there is no need for it. Unfortunately, the back glass is assumed to be of the same sort, namely low iron and high transparent, because of lack of alternative Ecoinvent glass data. Glass data in Ecoinvent come in many sorts such as bottles, tubes etc. but the most representative was data for solar panels, high transparent and low iron content. This means that the impact categories originating from the back glass will be slightly overrepresented. Since there is nothing to compare with, the scale of the overrepresentation is unknown. Generally, low iron glass and ordinary glass with higher iron oxide content, are processed in the same way, the difference being the absence of iron oxide in some silica sand compared to other[98]. The overrepresentation will thus be very small in comparison to the total impact from glass production.

See Appendix 3 for the unit process raw data.

High transparent low iron glass is used for the panels produced by Gaia Solar. The difference between the front and the back glass is the thickness. Front and back glass data is presented below.

Table 9: Front and back glass parameters.

Front glass thickness	0,0032 m
Back glass thickness	0,0040 m
Density low iron glass[99]	2507,60 kg/m^3
Panel glass area (one panel, front and back)	2,065 m^2
Total glass area (3 000 Wp system)	44,12 m^2
Front glass volume	0,0033 m^3
Back glass volume	0,0041 m^3
Front glass weight	8,28 kg
Back glass weight	10,35 kg
Total glass weight (3 000 Wp system)	385 kg

The density was required to enable recalculation from m^2 to kg which was the unit for Ecoinvent data. Ecoinvent data was then extrapolated by a factor of 385 times to represent the total glass for the PV system.

See the unit process raw data in Appendix 3 for more information.

3.1.7 Protective back sheet (PBS)

The protective back sheet is a rather thin layer consisting of several different substances in reality but because Ecoinvent did not have data for PBS, the decision was made to only include the mayor substance of EVE namely polyethylene. Data for polyethylene was available in Ecoinvent but as in the case of the encapsulate, the data was presented in kg of bulk material meaning that the process to press

[98] SPANCraft Glass, *Low iron glass*, 2014, retrieved 14 May 2014, <http://www.spancraft.com/low-iron-glass.shtml>
[99] NovoGlass, *Noval ultra clear low-iron glass,* retrieved 14 May 2014, <http://www.novalglass.com/DownLoad/Ultra-Clear-Float-Glass.pdf>

it into sheets is excluded. The same arguments are valid for PBS as were for the encapsulate. PBS data is presented below.

Table 10: PBS parameters.

PBS thickness	0,000250 m
Density[100]	23 kg/m^3
PBS area (one panel)	1,032 m^2
PBS total area (3 000 Wp system)	21,367 m^2
PBS volume	0,000258 m^3
PBS total volume	0,00560 m^3
PBS total weight	0,12 kg

In the production process of PBS, polyethylene is expanded to form a very light sponge-like sheet. The density and the weight are thus very low. Only 12% of the Ecoinvent data for PBS is taken into account.

Appendix 3 lists the unit process raw data for further information.

3.1.8 Anti-reflecting coating (AR-coating)

AR-coating data was available at Ecoinvent which means that no assumptions were made for the AR-coating process. It was convenient that data was presented in m^2 allowing for easy recalculation. AR-coating data is presented below.

Table 11: AR-coating parameters.

Panel area	1,032 m^2
Amount of panels	20,7
Total panel area	21,367 m^2

Ecoinvent data was extrapolated by 21,367 times in order to represent the case for a 3 000 Wp system.

Moore data can be found in the unit process raw data in Appendix 3.

3.1.9 Extraction and refining and production

Usually a product undergoes a series of refining steps from extracted resources in order to be produced. Ecoinvent data was available for whole sub-products to a PV system as shown in Figure 5. The data is presented for a whole product and includes all process stages and resource extraction needed for its production. Therefore all process steps for a product are taken into account by Ecoinvent and are therefore also included in the results of this study. Data for these sub-products is presented in Appendix 3 along with resource consumption. The production of solar cells was the only process described in detail with sub-processes as seen in Figure 9. All production and refining steps for the production of solar cells are presented in this study.

[100] DIYTrade, *Low density expanded polyethylene foam (EPE) roll*, 2008, retrieved 14 May 2014, <http://www.diytrade.com/china/pd/8559255/Low_density_Expanded_Polyethylene_Foam_EPE_Roll.html>

3.1.10 Resource consumption

Resources are represented for every sub-product included in the PV system by the Danish Ecoinvent data tool EDIP (Environmental Design of Industrial Products). The resources are presented below.

Table 12: Resource flow throughout the studied system based on EPID characterization resources. NRR stands for Non-Renewable Resource and RR stands for Renewable Resource.

	Panel							BOS			
(kg/kWh)	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport	Assembly	Inverter	Electric installation	Roof installation	Transport
NRR, aluminium	1,73E-05	2,21E-07	7,50E-07	2,20E-07	4,84E-12	4,90E-07	8,23E-10	1,99E-05	1,06E-06	3,15E-04	1,52E-07
NRR, antimony	1,98E-12	9,49E-16	2,04E-15	3,30E-16	2,59E-20	5,48E-14	3,44E-18	1,09E-14	1,47E-15	1,61E-14	2,14E-14
NRR, brown coal	4,63E-04	6,57E-05	8,63E-05	1,64E-05	7,56E-10	1,71E-05	1,45E-07	1,00E-03	1,43E-04	4,32E-04	4,88E-06
NRR, cadmium	1,39E-10	3,10E-11	9,52E-11	1,25E-11	7,67E-16	1,68E-09	1,56E-13	3,07E-10	3,70E-11	8,42E-10	4,90E-10
NRR, coal	3,18E-04	4,98E-05	1,41E-04	8,67E-05	1,68E-07	2,99E-05	1,05E-05	8,43E-04	1,29E-04	7,25E-04	8,61E-06
NRR, cobalt	1,08E-12	1,45E-13	7,53E-13	8,41E-14	3,84E-17	5,30E-12	1,71E-15	3,34E-11	3,39E-13	1,11E-11	1,77E-12
NRR, copper	9,73E-07	2,03E-07	6,09E-07	1,89E-07	2,21E-12	1,26E-07	6,24E-10	1,21E-04	1,07E-04	5,56E-06	3,94E-08
NRR, gold	6,17E-12	1,38E-11	1,93E-11	2,04E-12	9,96E-17	1,42E-11	2,14E-15	8,79E-09	2,94E-12	1,08E-11	4,40E-12
NRR, iron	2,98E-05	2,99E-06	8,71E-06	3,28E-06	3,55E-10	2,45E-05	5,54E-08	2,77E-04	1,46E-05	4,23E-04	7,01E-06
NRR, lead	8,45E-08	2,83E-09	6,52E-09	8,07E-09	9,01E-13	1,41E-07	1,59E-11	5,41E-07	4,47E-09	2,52E-07	5,52E-08
NRR, manganese	3,24E-07	1,86E-08	3,21E-08	6,10E-09	6,80E-13	1,58E-08	2,34E-10	3,69E-06	1,44E-07	5,84E-06	4,25E-09
NRR, mercury	6,76E-11	9,00E-13	1,07E-12	7,49E-13	4,33E-15	1,06E-12	8,47E-15	6,24E-11	9,51E-12	1,71E-10	3,40E-13
NRR, molybdenum	7,52E-08	4,01E-09	1,00E-08	2,99E-09	4,28E-14	2,39E-09	1,69E-11	2,02E-06	1,58E-06	2,74E-07	7,25E-10
NRR, natural gas	3,43E-04	1,50E-04	3,16E-04	7,14E-05	9,56E-07	2,12E-05	2,22E-06	4,05E-04	1,66E-04	1,93E-04	6,61E-06
NRR, nickel	1,97E-06	4,29E-07	5,66E-07	1,19E-07	4,05E-12	2,22E-07	3,51E-09	2,02E-05	3,90E-06	2,27E-05	6,15E-08
NRR, oil	1,32E-04	2,29E-04	2,41E-04	1,10E-05	1,49E-06	2,38E-04	5,19E-07	3,03E-04	2,20E-04	3,71E-04	7,40E-05
NRR, palladium	6,92E-13	6,20E-13	1,68E-12	1,40E-13	9,05E-18	1,23E-12	2,70E-15	3,37E-12	2,94E-13	4,79E-12	3,82E-13
NRR, platinum	1,81E-13	1,63E-14	4,89E-14	4,03E-14	3,29E-19	3,25E-14	4,81E-15	2,37E-13	3,39E-14	2,31E-13	1,06E-14
NRR, silver	1,82E-06	3,71E-11	5,19E-11	5,55E-12	2,69E-16	3,80E-11	6,31E-15	3,12E-07	8,41E-12	3,07E-11	1,18E-11
NRR, tantalum	6,45E-12	1,35E-11	1,88E-11	2,01E-12	9,75E-17	1,38E-11	2,25E-15	5,68E-07	3,01E-12	1,10E-11	4,28E-12
NRR, tin	7,62E-10	5,94E-10	1,74E-07	1,40E-10	6,07E-15	6,78E-10	2,19E-12	1,45E-06	4,29E-10	1,33E-09	2,06E-10
NRR, zinc	1,61E-07	7,54E-08	2,32E-07	3,08E-07	2,53E-11	9,83E-08	4,03E-11	3,03E-06	5,93E-07	1,57E-07	2,92E-08
RR, wood	8,49E-08	3,55E-08	4,70E-08	3,66E-08	8,99E-14	2,35E-09	3,83E-09	1,86E-07	1,65E-08	6,00E-08	7,21E-10
SUM	1,31E-03	4,98E-04	7,95E-04	1,90E-04	2,61E-06	3,32E-04	1,34E-05	3,00E-03	7,86E-04	2,49E-03	1,01E-04

The resource consumption is presented per fiction unit (FU), which is kWh, for a 30 years lifetime of the PV system. All parts of the PV system are resized/extrapolated to the representative extent for the studied PV system. Resources for front and back glass, along with the aluminum in roof installation, are further managed to represent recycling of these parts. Processes which don’t include the use of new physical resources, such as the assembly, still result in resource consumption. This is due to the electricity production and the construction, operation and service of power plants.

3.1.11 Energy flow

The energy flow throughout the studied system, from part manufacturing to transportation and assembly, is presented below. The energy mix for the majority of parts and processes are represented for European electricity mix except for the assembly stage. The assembly represents the electricity mix that is used by Gaia Solar. It is a combination of Danish electricity mix with own solar generated electricity. Approximately 54% of the yearly electricity consumption is generated from solar power.

Table 13: Energy flow for the studied system. NRE stands for Non-Renewable Energy and RE stands for Renewable Energy.

	Panel					BOS			Transport	Panel
kWh/kWh	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Inverter	Electric installation	roof installation	Transport	Assembly
RE, biomass	0,00443334	0,000110772	0,000248108	0,000104916	1,42287E-07	0,00053317	6,16197E-05	0,000456512	1,21E-05	2,67637E-06
NRE, fossil	0,14450725	0,005348038	0,016502963	0,001595477	3,25089E-05	0,01647091	0,006082459	0,032579898	0,005973	2,73109E-05
NRE, nuclear	0,04595595	0,000506793	0,001182077	0,000132622	2,19315E-06	0,0062648	0,001197393	0,008333021	0,000409	2,41889E-07
NRE, primary forest	1,3757E-06	1,35395E-08	4,65579E-08	2,79978E-07	4,36059E-14	1,0433E-07	5,49587E-09	1,6663E-07	1,89E-08	9,7232E-12
RE, solar, converted	1,183E-05	1,07397E-07	2,8989E-07	4,0549E-08	1,34897E-12	1,5729E-06	2,2919E-07	7,47368E-07	6,46E-08	8,82378E-05
RE, water, converted	0,02830673	5,6771E-05	0,000221809	3,70865E-05	2,65888E-07	0,00115095	0,000310197	0,006921179	7,94E-05	5,12878E-08
RE, wind, converted	0,00085929	7,51066E-06	1,99191E-05	5,67395E-05	8,72381E-11	0,00011047	1,60025E-05	5,25189E-05	3,37E-06	2,01613E-05

3.2 Degradation

Degradation of the PV panels affects the whole performance of the PV system. Below is a graph of how the degradation proceeds. After 30 years the installed power has reduced to 2,59 kWp from the initial 3 kWp. If the PV system reaches a lifetime of 40 years the installed power would correspond to 2,47 kWp. The specific annual yield is constant at 925 kWh/kWp throughout the lifetime of the solar panel.

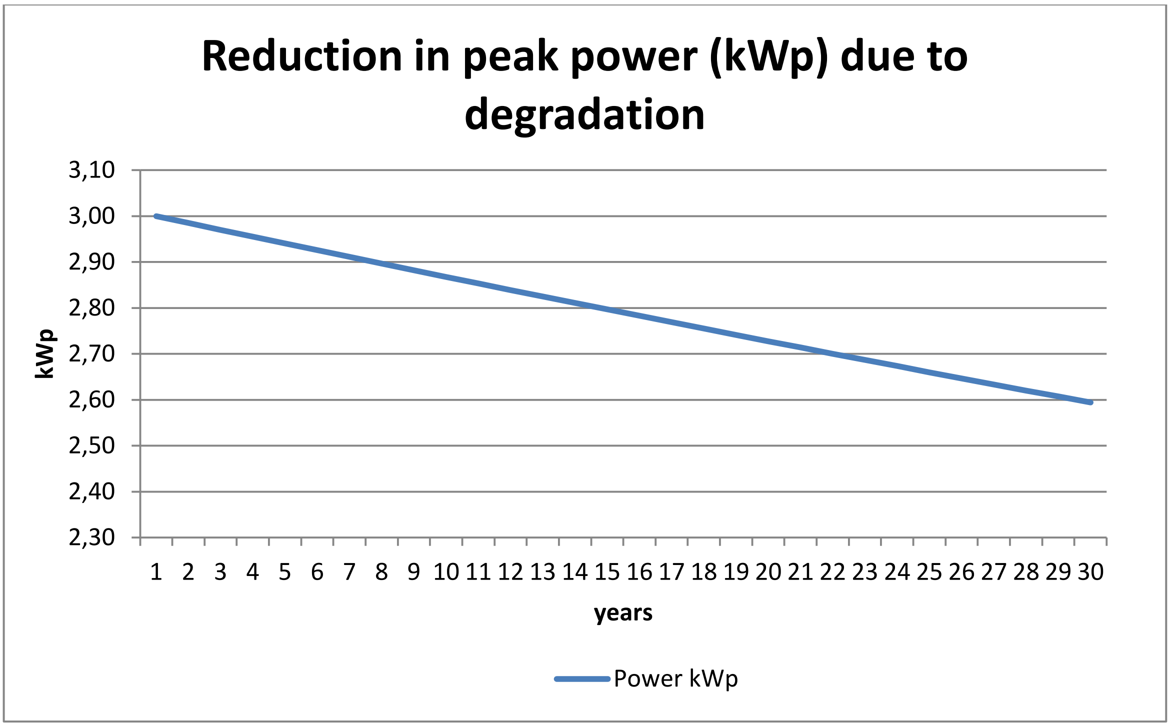

Figure 12: Degradation rate of the initially installed 3 kWp PV system.

3.3 Energy output from the PV system

Energy conversion by the PV system is directly linked to the irradiation and the installed power. With a constant specific annual yield and the degradation presented above, the electricity generation of the PV system throughout its lifetime is reduced in the same rate. The total energy output after 30 years is

77 487 kWh. This value enables the use of the function unit. All results are divided by the lifetime energy generation to obtain a final value of kg X-quivalents/kWh, or per FU since they are the same.

In case the PV system endures 40 year with degradation included, the energy output would be 100 832 kWh. That is a huge addition compared to the 30 years case and a good demonstration of the possible gains by producing more durable PV system.

3.4 Transport

Transportation between different locations during the refining and production of the product are included within the Ecoinvent data for each sub-product of the PV system. The transportation will thus be included in the impact categories up to the stage where the sub-products are finished.

Because the sub-products are assembled in Denmark, transportation data form the production plant to Denmark is not included in Ecoinvent data for sub-products of the PV system. This must be conducted separately. A lot of assumptions can be made regarding the transportation. Most of the production sites are in Europe but are not stated specifically where. An assumption is therefore made to represent the real locations of the suppliers to Gaia Solar. This is after all the most representative way. Google maps is used in the calculation of distance and supplier locations are provided by Gaia Solar.

The transportation trip is assumed to be one way only. The return of the transportation trucks and ship are assumed to carry other goods and provide other services. An exception is the transportation from Gaia Solar to the location of the PV system, where the vehicle is assumed to return empty. This is also included in the calculations.

3.4.1 Ecoinvent transport data

This additional and separate final transportation data is also gathered from Ecoinvent and specified for the type of transportation used in this study. This study includes three types of transportation namely trans-oceanic freight ship, lorry 16-32 tons and EURO 5 standard and lorry 3,5-7 tons and EURO 5 standard. Since the majority of the sub-products to the PV system are produced in Europe the transportation of choice is assumed to be a heavy-duty lorry, 16-32 tons. The choice for transportation of the PV system to its location from the assembly site is a smaller lorry with purpose to only deliver the system to the location.

Presented data in Ecoinvent include aspects such as operation, construction and maintenance of the transportation vehicle and vessel and also port and road construction[101,102]. More about this can be found in the metadata for the transport in Appendix 4.

[101] Ifu Hamburg, *Ecoinvent: Transport – what is the difference between operation and transport in the lorry database*, retrieved 15 May 2014, <https://www2.ifu-hh.de/otrs/public.pl?Action=PublicFAQZoom;ItemID=37>
[102] Ecoinvent data base, *unit process raw data, transport*.

3.4.2 To and from location

This study is conducted for Danish local conditions regarding solar irradiation and energy for assembly and thus consistency and logic dictates that the location of the reference system of this study, 3 000 Wp solar system installed on a slanted roof, ought to be near Copenhagen, Denmark. A distance of 50 km is assumed from the assembly location at Gaia Solar to the installation site for the PV system. Since measured irradiation and electricity generation values in this study are measured at Gaia Solar, it would be convenient if the assumed location for the PV system is also within these parameters.

A solar irradiation map of Denmark[103] is used when assumption of 50 km is made. There are of course other locations in Denmark with the same irradiation magnitudes as at the assembly plant. Nevertheless the location of the installed PV system is assumed to be quite close to Copenhagen and thus the assembly plant at Gaia Solar.

When the PV system is due to be disposed and recycled, it is sent to the nearest recycling point for such purposes which is located in Skanderborg, Denmark[104]. The transportation is by heavy-duty lorry 16-32 tons with the assumption that it only accounts for one way trip.

3.4.3 EURO 5

The European Union is working continuous with imposing stricter and tougher demands on the transportation vehicles in EU with the intention to lower greenhouse gas, particles and other emissions. The regulations effect mostly particle emissions and nitrogen oxide emissions[105].

Available data from Ecoinvent of EURO 5 class is used in this study. The vehicles fulfill the requirements of EURO class 5 which are shown in the table below.

Table 14: EU emission standards for heavy-duty diesel engine vehicles. Source: Transportpolicy.net, EU: Heavy-duty: Emissiona, http://transportpolicy.net/index.php?title=EU:_Heavy-duty:_Emissions.

EU Emission Standards for HD Diesel Engines, g/kWh (smoke in m^{-1})

Tier	Date	Test	CO	HC	NOx	PM	Smoke
Euro I	1992 (< 85 kW)	R-49	4.5	1.1	8.0	0.612	
	1992 (> 85 kW)		4.5	1.1	8.0	0.36	
Euro II	October 1996		4.0	1.1	7.0	0.25	
	October 1998		4.0	1.1	7.0	0.15	
Euro III	*October 1999 (EEVs only)*	*ESC & ELR*	*1.5*	*0.25*	*2.0*	*0.02*	*0.15*
	October 2000	ESC & ELR	2.1	0.66	5.0	0.10 0.13[a]	0.8
Euro IV	October 2005		1.5	0.46	3.5	0.02	0.5
Euro V	October 2008		1.5	0.46	2.0	0.02	0.5
Euro VI	January 2013	WHSC	1.5	0.13	0.4	0.01	

Notes:
a - for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}
EEV - enhanced environmentally-friendly vehicles

[103] European Commission, op.cit.,
[104] PV Cycle, *Find a collection point*, 2013, retrieved 15 May 2014, <http://www.pvcycle.org/collection-points/map/>, location: Skanderborg, Horsensvej 91-93
[105] Europa, *Sammanfattning av EU-lagstiftning*, 2013, retrieved 15 maj -14, <http://europa.eu/legislation_summaries/environment/air_pollution/l28186_sv.htm>

3.4.4 Transportation additional information

Following information describes the real supplier locations and not random European location assumed from Ecoinvent. Transoceanic freight ships are assumed to dock at Hamburg port and the remaining distance is assumed to be covered by Lorry 16-32 tons.

Solar cells

Solar cells are transported from Taiwan and are assumed to be so by freight ship to Hamburg, and thereafter with lorry 16-32 tons.

Inverter

The inverter is produced in Nordborg, Denmark.

Front Glass and AR coating

Since AR-coating data in Ecoinvent is from Denmark and the high transparent low iron front glass suppliers are also from Denmark at a known location, they both are assumed to be delivered from the same location.

Back glass

Back glass is produced in Lommel, Belgium.

Electric installation

Electric installation contains several different parts such as junction box, cables and meters. Because Ecoinvent data is presented in a package, including all parts, it is reasonable to assume that all real parts are shipped from the supplier location of the most dominant part included in electric installation. For instance, if the cables make up 80% of the electric installation and are produced and shipped from Berlin, Germany, while the actual meters are produced and shipped from Denamrk, the assumption dictates that the whole electric system will be shipped from Berlin.

Roof installation

Roof installation also consists of several parts such as screws, fasteners, aluminum rails and more. Aluminum rails are the dominant on these parts and therefore all other roof installation parts correspond to a small part of the total roof installation. It is thus assumed that all parts originate from the location of aluminum rail suppliers. It is assumed to be produced within Denmark.

Encapsulate (EVA)

EVA is produced in Llanera, Spain.

Protective back sheet

The PBS is produced in Boston, USA, and is assumed to be shipped to Hamburg (DE) by freight ship. From there on PBS will be transported to Copenhagen by lorry 16-32 tons.

PV system

The whole PV system is, as mentioned earlier, transported to a location within Copenhagen.

PV system recycling and disposal

The closest collection point for disposal/recycling of the PV system is regarded in this study, which is Skandeberg, Denmark[106]. Transportation from the collection point to a treatment plant is not included in this LCA. It is regarded as if the PV system is recycled and disposed at the collection point.

3.4.5 Transport parameters freight ship

Table 15: Transport parameters regarding solar cells from Taiwan.

Type	Description	Trip	Weight (tons)	Distance (km)	Ton*km (tkm)	Extrapolation factor (times)
Freight ship	Solar cells	Taiwan (CH)-Hamburg (DE)	0,01	29000	290	290
Freight ship	Protective back sheet	Boston (US) – Hamburg (DE)	0,0002	6000	1,2	1,2
Freight ship	**SUM**					**291,2**

These are the only parts of the PV system, transported by trans-oceanic freight ship. Since Ecoinvent data is presented in 1 tkm (ton-kilometers) it is extrapolated 291,2 times for this study. The weight of the transported product is rounded up to include packaging materials.

Unit process raw data from Ecoinvent for the freight ship transportation is presented below in table 14 as well as meta-information from the producer of the data in Ecoinvent, in Appendix 4.

As noted, data such as operation, production and maintenance of the ship, port construction and maintenance, is included. Separate LCA inventories from cradle-to-grave, about these stages, are the source for the presented results. Alongside the inventory data, assumptions are made based on statistics for the operation of one port in Netherlands. Since two ports are needed, to be able to transport a product, the two ports are assumed to be identical as the one in Netherlands. Vessel manufacturing LCA results are allocated to the expected distance traveled by a freight ship during its lifetime, 2 000 000 km. Environmental load is based on a yearly result, then allocated per trip. Further descriptions are presented in the metadata for freight ship transportation in Appendix 4.

[106] PV cycle, collection points, http://www.pvcycle.org/collection-points/map/

Table 16: Unit process raw data for freight ship transportation per tkm relative to the total production, maintenance and operation.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	transport, transoceanic freight ship
			Location						OCE
			InfrastructureProcess						0
			Unit						tkm
Technosphere	5		operation, transoceanic freight ship	OCE			0	tkm	1
	5		transoceanic freight ship	OCE			1	unit	1,54E-11
	5		maintenance, transoceanic freight ship	RER			1	unit	1,54E-11
	5		port facilities	RER			1	unit	1,27E-14
	5		operation, maintenance, port	RER			1	unit	1,27E-12
Outputs		0	transport, transoceanic freight ship	OCE			0	tkm	1

3.4.6 Transport parameters lorry 16-32 tons, EURO 5

Table 17: Parameters for transportations of sub-products for a PV system to the assembly site in Copenhagen.

Type	Description	Trip	Weight (tons)	Distance (km)	Ton*km	Extrapolation factor (times)
Lorry 16-32 tons	Solar cells	Hamburg (DE) – Copenhagen (DK)	0,01	334	3,34	3,34
Lorry 16-32 tons	Inverter x2	Nordborg (DK) – Copenhagen (DK)	0,04	350	14	14
Lorry 16-32 tons	Front glass and AR-coating	Sorring (DK) – Copenhagen (DK)	0,17	304	51,68	51,68
Lorry 16-32 tons	Back glass	Lommel (BE) – Copanhagen (DK)	0,22	826	181,70	181,70
Lorry 16-32 tons	Electric installation	Berlin (DE) – Copanhagen (DK)	0,03	442	13,26	13,26
Lorry 16-32 tons	Roof installation	Denmark – Copenhagen (DK)	0,1	200	20,09	20,09
Lorry 16-32 tons	Encapsulate (EVA)	Llanera (ES) – Copenhagen (DK)	0,02	2603	52,06	52,06
Lorry 16-32 tons	Protective back sheet	Hamburg (DE) – Copenhagen (DK)	0,0002	334	0,067	0,067
Lorry 16-32 tons	PV system deposition and recycling	Copenhagen (DK) – Skanderborg (DK)	0,50	274	137	137
Lorry 16-32 tons	**Sum**					**473,20**

The lorry transportation includes similar stages as the freight ship transport did, such as operation, maintenance, disposal etc. Allocation for a trip, by Ecoinvent, is made based on the estimated distance during the lifetime of the lorry. For more information see unit process raw data in Appendix 3 and metadata in Appendix 4.

The total Ecoinvent data for the transportation by lorry 16-32 tons, is extrapolated 473,2 times in order to represent all transports by this type of vehicle.

3.4.7 Transport Parameters lorry 3,5-7,5 tons, EURO 5

Parameters about the transport with the lorry 3,5-7,5 tons follow below.

Table 18: Transport parameters for the delivery of PV system to installation location.

Type	Description	Trip	Weight (tons)	Distance (km)	Ton*km	Extrapolation factor (times)
Lorry 3,5-7,5 tons	Whole PV system	Copenhagen – Copenhagen area	0,5	100	50	50

Since Ecoinvent data for the lorry is presented in tkm, it is extrapolated by 50 times to represent the transportation of the PV system. Weight is rounded up in order to represent the packaging materials. The reason for the large distance is because the lorry travels 50 km to the location and then returns. It is therefore a two way trip.

Unit process raw data from Ecoinvent, representing transport by lorry 3,5-7,5 tons, is presented below in table 19 and follows the same methodology as previous transport parameters for heavy-duty lorry and freight ship. There are some differences regarding assumptions of operation, maintenance and infrastructure. The operation and disposal of the vehicle as well as the infrastructure represent Swiss conditions. Allocation regarding the production, maintenance and disposal of roads is made by gross tkm transported on it. The lifetime expectancy of the vehicle is assumed to be 540 000 vkm (vehicle-kilometers). Further detailed metadata is accessible in Appendix 4.

Table 19: Unit process raw data for Lorry 3,5-7,5 tons transportation per tkm relative to the total production, maintenance and operation.

Explanations	Input-Group	Output-Group	Name	Location	Infrastructure-Process	Unit	transport, lorry 3.5-7.5t, EURO5
			Location				RER
			InfrastructureProcess				0
			Unit				tkm
Technosphere	5		operation, lorry 3.5-7.5t, EURO5	RER	0	vkm	1,0206
	5		lorry 16t	RER	1	unit	1,89E-06
	5		maintenance, lorry 16t	CH	1	unit	1,89E-06
	5		disposal, lorry 16t	CH	1	unit	1,89E-06
	5		road	CH	1	ma	2,89E-03
	5		operation, maintenance, road	CH	1	ma	1,20E-03
	5		disposal, road	RER	1	ma	2,89E-03
Outputs		0	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	1

3.5 Assembly at Gaia Solar

The assembly process begins with quality check of the solar cells by exposing them to a light source in order to conclude that the output energy is in line with the expected results. When the cells are approved they are interconnected with a tape string machine before being placed out in the correct pattern for the soldering. When the cells are aligned correctly and connected, they are laminated by a lamination machine. While the cells are laminated, the junction box, which is a part of the electric installation and joins the solar cell connection strings to extern cables, is mounted on the back glass. The front and back glass are also polished, cleaned and prepared to be combined with the solar cells, encapsulate and the protective back sheet. After the assembly of the panels, they are tested on a solar simulator in order to determine that everything is working as expected. That was also the last step of the panel assembly process before the panels are shipped to the customers.

3.5.1 Energy at Gaia alone

The energy required for the assembly process at Gaia Solar is assumed to be the same as in IEA PVPS Task 12, which is 10,7 kWh for the amount of panels included in a 3 000 Wp PV system. Due to several reasons, an actual measurement could not be performed and thus the use of extern assembly data.

The energy for assembling of the PV panel does not correspond to standard Danish electricity mix. The reason for that is because Gaia Solar generate own electricity from installed solar panels. The company produces 54% of the total yearly electricity consumption. The production of electricity is assumed to be for own use despite the fact that electricity is generated at after work times and exported to the grid. The remaining 46% of the electricity represents Danish electricity mix. Ecoinvent data was used for the Danish electricity mix in combination with extended solar power generation in order to represent the assembly at Gaia Solar. The results for the Danish electricity mix are presented in the table below.

Table 20: Final results for the electricity mix used by Gaia Solar.

renewable energy resources, biomass	0,26	kWh
non-renewable energy resources, fossil	2,55	kWh
non-renewable energy resources, nuclear	0,03	kWh
non-renewable energy resources, primary forest	0,00	kWh
renewable energy resources, solar, converted	7,86	kWh
renewable energy resources, potential (in barrage water), converted	0,00	kWh
SUM	10,74	kWh

3.6 Deposition and recycling

After thorough examination of Ecoinvent data, it is clear that deposition is assumes after the lifetime of the parts incorporated in the PV system. This does not correspond to the reality since Gaia Solar recycles used PV panels to a PV recycling company in Holland. Thus energy and materials are reused after processing to obtain new products.

Such a recycling process relies upon data about what and how much of the panel is recycled and what and how much is incinerated and/or deposited. Generally a LCA about recycling is needed of that company in order to be able to include the recycling/waste phase in this LCA study. Fortunately such a study is available.

By including recycling of materials in the study, the final results will be lower than if no recycling was carried out. This is due to the fundamental idea behind recycling, namely spearing new extraction of materials, and even purification of extracted materials, by recycling the used material back in the production chain. Recycled material replaces the use of new material and thus spearing and lowering the impact (environmental, energy, economic etc.) of the product, compared to if the product did not include recycled materials.

3.6.1 Recycling LCA

The recycling company, cooperating with Gaia Solar, is called PV Cycle. PV Cycle in cooperation with Maltha Glass Recycling has made a LCA regarding recycling of PV modules after user phase. The data obtained by their research will be used in this LCA study in order to obtain as accurate final results as possible.

Due to extensive information regarding the recycling LCA, the reader is referred to the web-address of the study at: *http://www.pvcycle.org/wp-content/uploads/Fraunhofer_3rd-RC_2013.pdf*. In this study only brief results and important parameters will be described further. All result about recycling of PV modules will be included in the final results of this LCA, thus slightly lowering the environmental burden for the whole PV system.

The process flowchart for the recycling of PV panels is presented in figure below.

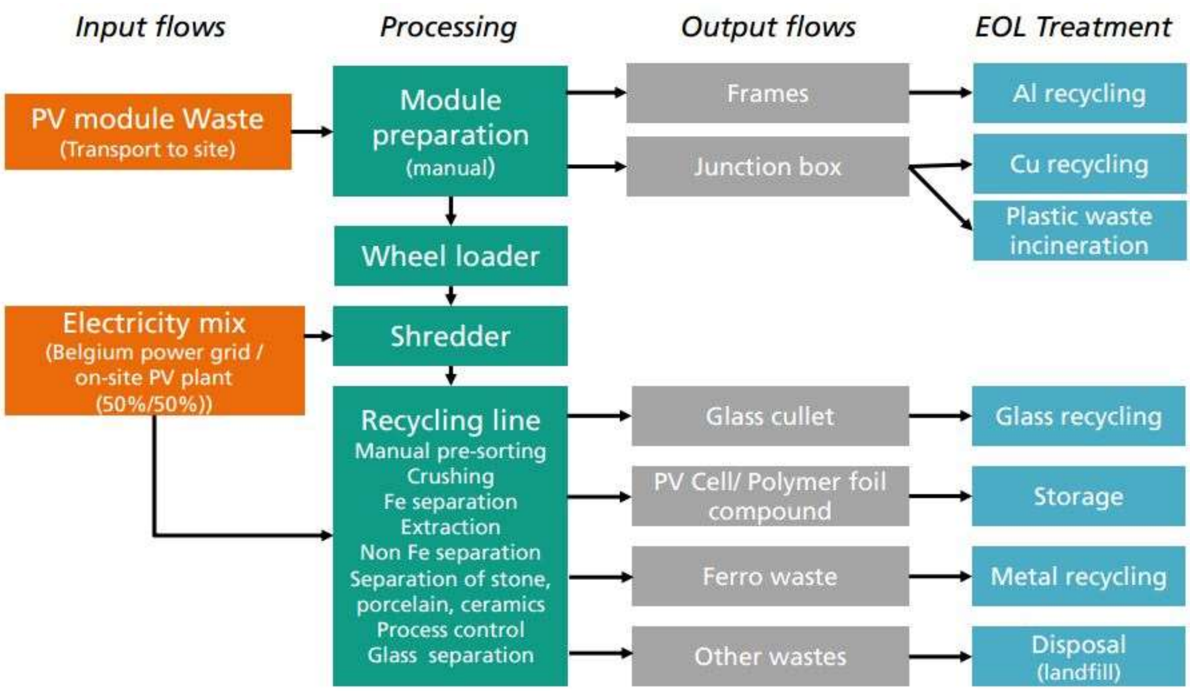

Figure 13: Flowchart for the recycling process of PV modules. Source: Executive summery, Life cycle assessment (LCA) screening of the Maltha recycling process for si-pv modules.

The LCA study analyzed three different scenarios for recycled content as a percent of a PV module. The first scenario compares the recycling benefits of a PV module produced only from non-recycled, new primary materials (100 % primary resources). The other two scenarios analyzed a PV module assumed to be produced from 50 % primary resources and 10% primary resources respectively. Ecoinvent data is based on primary resource consumptions and thus the case for 100% primary resources is representative for this study. See figure 14 for clarification.

According to the recycling LCA, all environmental, resource and energy expenses of recycling are accounted for. Energy gains from incineration of some parts are included but not the recycling of these parts, since they are incinerated.

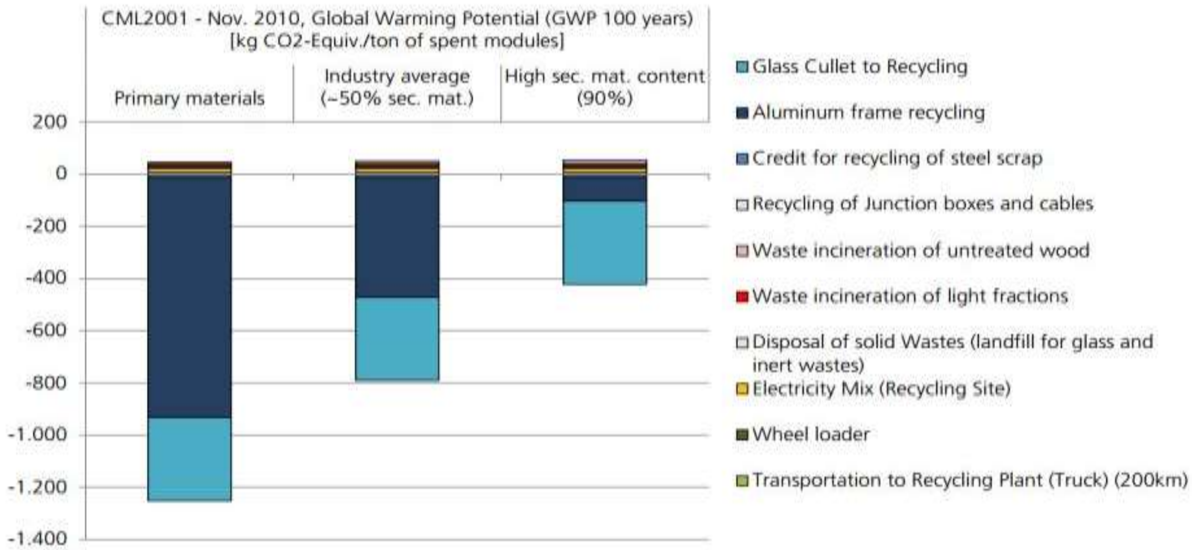

Figure 14: Global warming potential for a PV module. Source: Executive summary, Life cycle assessment (LCA) screening of the Maltha recycling process for si-pv modules.

3.6.2 Recalculation for aluminum recycling of roof installation

Presented results from the recycling LCA are also applicable for the calculation of the roof structure. Presented data from recycling LCA for the aluminum frame will be used in order to calculate the aluminum rails in the roof installation. Thorough calculations are presented in Appendix 1. It is assumed that the production for aluminum rails and aluminum frame processes are identical. Actual data from Gaia Solar is used.

The results in LCA recycling include data about the aluminum frame and by knowing its mass, one can calculate the impact reduction. When the impact, per mass aluminum, is known it could be applied to the mass of aluminum for the roof installation and thereby resulting in recycling values for the roof installation.

Because the roof installation does not only consist of aluminum, it had to be known how much of the roof installation mass consists of aluminum. Afterwards, aluminum weight fraction is separated from roof installation data in order to be recalculated with recycling. When recycling of the aluminum is recalculated, the new data is added back to the remaining roof installation data and thus resulting in total final impact results of the roof installation, where the aluminum parts are recycled.

Data which enabled recalculations was obtained from the results of the recycling LCA presented below in figure 15 and in figure 14. The results include impact categories used in this LCA study as well, and can thus be used. Almost all environmental impact categories are presented with one exception, namely the ozone depletion potential. The author of the recycling LCA have not included ozone depletion potential and has instead included photochemical ozone creation potential. An assumption is made for the ozone depletion potential based on the lowest presented result, namely eutrophication potential with 40%. The reason for choosing the lowest presented value and assuming that for the ozone depletion potential is due to moral standards, and to address speculation about dishonesty and data manipulation for beneficial results.

When the missing value is assumed, the whole environmental impact section for this study is complete. Remaining impact categories such as human effect, land and water use are not included in the recycling LCA either, and will thus not be included in this study as well. There will be no impact gains for these categories due to recycling.

The resource category was modified for some resources in order to be more representative. Amongst the materials affected are aluminum and all energy resources such as coal, natural gas etc. Mentioned materials were reduced by 62,2 % in order to correspond to the recycled aluminum and speared energy from excavating new aluminum. All other materials in the resource category remain unchanged.

Figure 15 presents the percentage of reduced impacts from aluminum and glass recycling.

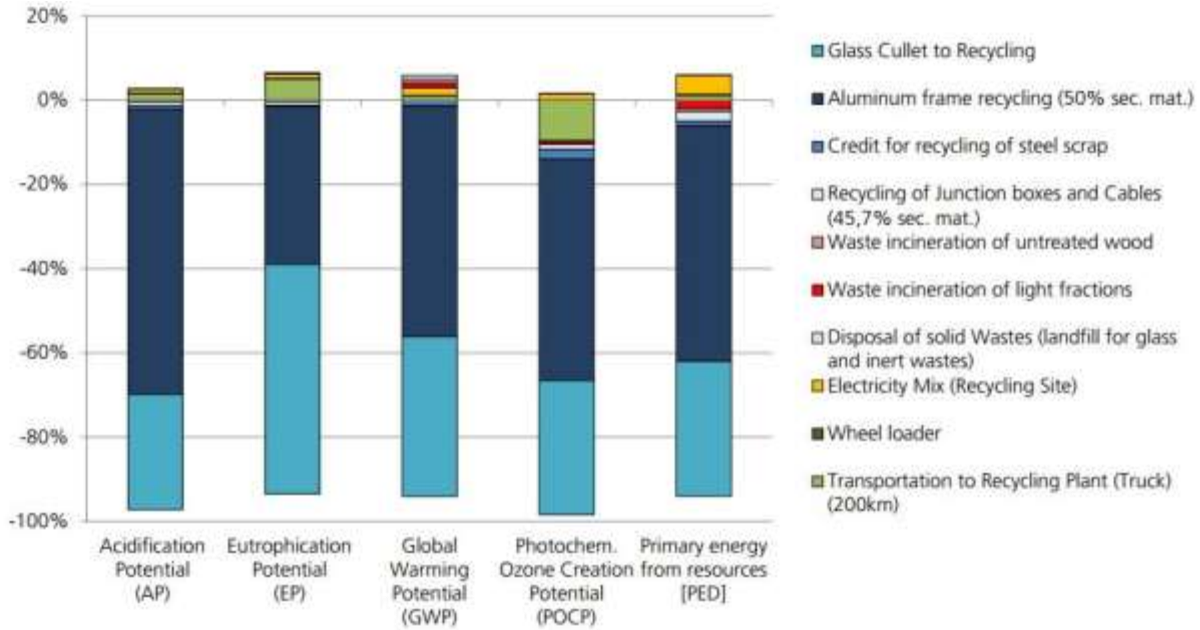

Figure 15: Results for different impact categories when PV module is recycled. The biggest parts are aluminum (dark blue) and glass (light blue).Source: Executive summary, Life cycle assessment (LCA) screening of the Maltha recycling process for si-pv modules.

Table 21: Environmental impact potential data for the recycled aluminum, the remaining parts and the total final values for a whole roof installation with aluminum recycling. Presented data is in kg units.

	Final aluminum	Rest materials	Sum, total roof installation with Al recycling	
	Roof installation	Roof installation	Roof installation	Unit
Acidification Potential	0,66	1,48	2,14	kg SO_2-eq.
Global Warming Potential, 100 years	200,99	326,81	527,80	kg CO_2-eq.
Eutrophication Potential	0,65	0,72	1,36	kg NO_x-eq.
Ozone Depletion Potential, 10 years	1,98E-05	2,2E-05	4,18E-05	kg CFC-11-eq.

Table 21 above presents the environmental impact values for the new modified roof installation where the aluminum rails are recycled, according to described methodology.

3.6.3 Recalculation for energy by recycling of aluminum in roof installation

The same method is used to calculate the final energy from the roof installation after including gains in energy from recycling of aluminum in roof installation. Because the recycling LCA only presents energy as a whole category and not as detailed as in this study (per source of energy), all the energy sources will be reduced in equal amount. It is as if all separately presented energy sources in this LCA are added up like the recycling LCA and then recalculated. Each source will thus be lowered by the same percentage. The percentage of energy gain by recycling is obtained from LCA recycling diagram shown in figure 15.

The table below is obtained through the same methodology as the aluminum recycling above was obtained. The recalculation steps will thus not be presented here and only the final result will. The final energy use for production of roof installation with recycled aluminum is presented below under the section “final”. For further information see Appendix 1.

Table 22: Energy reduction as a result of recycling aluminum in the roof installation. The most right column is the final result and the data used in this LCA. Final data is in kWh units.

(kWh)	Original roof Installation, total	Original aluminum only	Original remaining	saved aluminum %	saved aluminum	final aluminum	final total roof installation, final aluminum + Original remaining
renewable energy resources, biomass	35,37	22,00	13,37	62	13,64	8,36	21,73
non-renewable energy resources, fossil	2524,59	1570,29	954,29	62	973,58	596,71	1551,00
non-renewable energy resources, nuclear	645,72	401,63	244,08	62	249,01	152,62	396,70
non-renewable energy resources, primary forest	0,012	0,0080	0,0048	62	0,0049	0,0030	0,0079
renewable energy resources, solar, converted	0,057	0,036	0,021	62	0,022	0,013	0,035
renewable energy resources, potential (in barrage water), converted	536,31	333,58	202,72	62	206,82	126,76	329,49
renewable energy resources, kinetic (in wind), converted	4,06	2,53	1,53	62	1,56	0,96	2,50

3.6.4 Recalculation of front and back glass with recycling

The recalculation for glass recycling is much easier to conduct since it is presented in only glass data in Ecoinvent, contrary to the aluminum in roof installation. The calculations are performed in the same way as for the aluminum in roof installation. Results of the total glass for a 3 000 Wp system are presented below along with savings and percent of reduction from figure 15.

Table 23: Environmental impact potential data for the non-recycled glass, percent of reduction due to recycling, saved impact due to recycling and the final impact from glass used in this study. Presented data is in kg units.

	Original	reduction in %	Saved	Final
GWP, kg CO2-Eq	377,02	40	150,81	226,21
AP, kg SO2-Eq	3,27	25	0,82	2,45
EP, kg Nox-Eq	2,12	55	1,17	0,96
ODP. Kg CFC-11-Eq	4,60E-05	40	1,84E-05	2,76E-05

The recycling process spears the production and excavation of new resources in order to obtain glass thus lowering the total environmental impact from glass production.

Due to lack of impact categories for human effect, resources, water and land use in the recycling LCA, the gains from recycling will not be implemented on those categories.

3.6.5 Recalculation of energy with recycling of glass

The energy calculations are conducted in the same way as the case for aluminum and are presented below. According to the results of recycling LCA study the energy required for extraction of raw material is saved by 33%.

Table 24: Final results, on the most right column, of energy required for production of glass when recycling is included. Final units are in kWh.

(kWh)	Original	%	Saved	Final
renewable energy resources, biomass	19,23	33	6,34	12,88
non-renewable energy resources, fossil	1278,76	33	421,99	856,77
non-renewable energy resources, nuclear	91,59	33	30,23	61,37
non-renewable energy resources, primary forest	0,0036	33	0,0012	0,0024
renewable energy resources, solar, converted	0,022	33	0,0074	0,015
renewable energy resources, potential (in barrage water), converted	17,19	33	5,67	11,52
renewable energy resources, kinetic (in wind), converted	1,54	33	0,51	1,034

4 Results

Corresponding Life Cycle Inventories (LCI) for the chosen impact categories, seen in section 2.7, have been calculated by the characterization methods mentioned earlier. All Life Cycle Impact Assessment (LCIA) results for the impact categories in this study are presented in the coming sections. All data is also presented in Appendix 5, where all stages for the solar cell production are aggregated to one title named “solar cells”.

All results are presented as sub-products to the solar cells. They have also been denoted with “BOS” and “Panel” in order to clarify what category they belong to. An alternative would have been to present BOS, panels and transportation only but then the detail level is drastically reduced. In such diagrams, it would be impossible to see the amount of contribution from sub-products such as solar cells, inverter, encapsulate, etc.

All results, except for the EPBT and Speared emissions in Danish electricity mix, are presented per function unit. Results for the impact categories represents a 30 year lifetime of the system. The 40 years scenario is presented after the impact category results in section 4.7,

The choice for the majority of the diagram types, is based on the desire to present diagram columns as well as numeric results. This is due to small emission being dominated by larger ones and thus hard to read.

4.1 Resources

Resources consist of 6 impact categories as seen in section 2.8.

4.1.1 Resource consumption

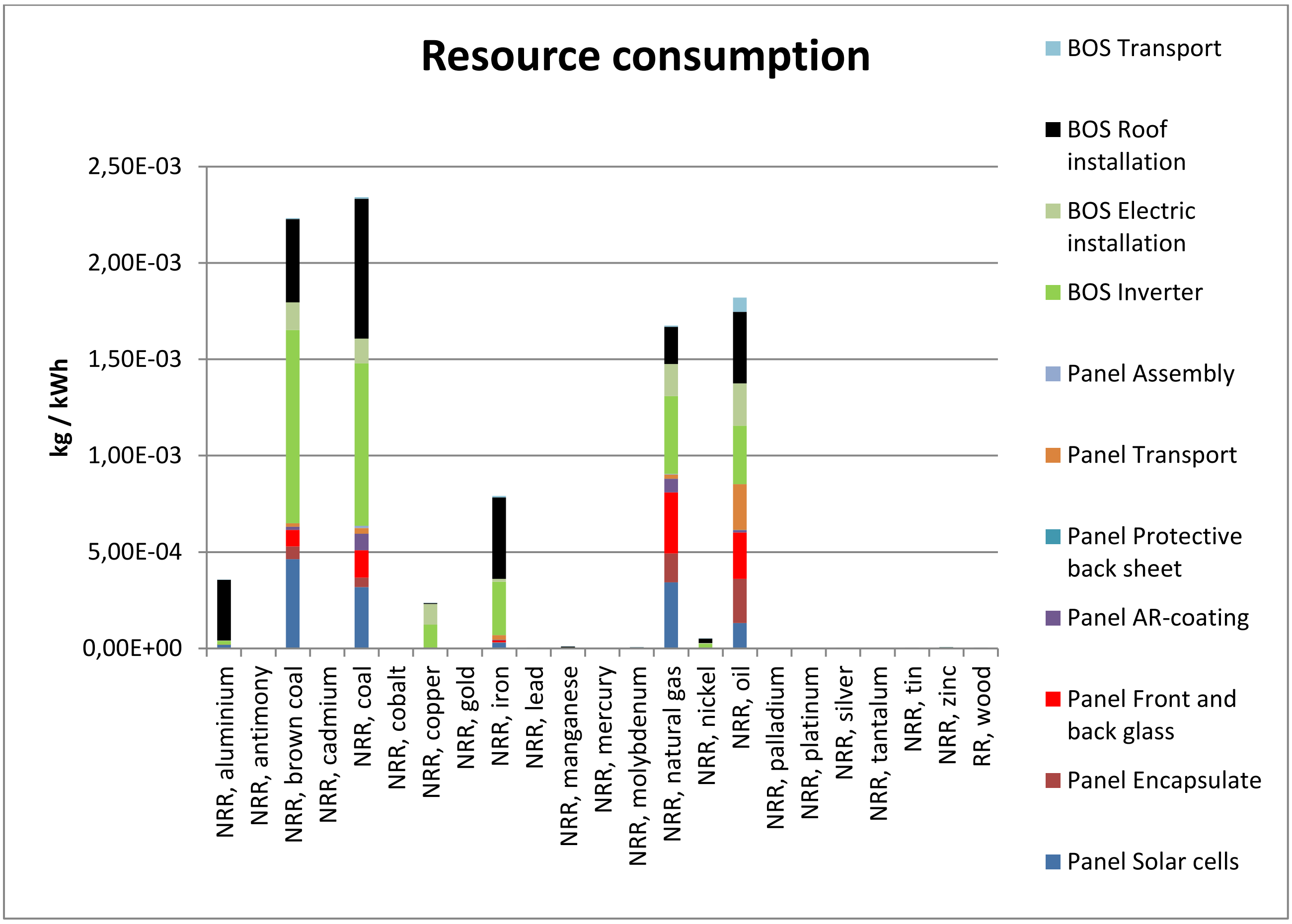

Figure 16: The amount of resources required for production of 3 000 Wp PV system. NRR stands for non-renewable resources and RR stands for renewable resources. The description, on the right side, represent the arranging of the diagram columns in falling order, BOS transportation highest up and Panel solar cells at the bottom. All results are presented per FU.

This diagram enables the identification of which and what amount of a resource is used to produce the sub-products for a PV panel, BOS and the whole PV system. Thorough analysis of the diagram also reveals which sub-products are the most resource demanding. For the PV panel, the cells that are most resource demanding followed by glass, encapsulate, AR-coating and last the protective back sheet. Note that not all resources are included in the Ecoinvent EDIP characterization method. Sand for instance is not included, but if it were the resource would probably be ruled by glass production.

The four highest results, brown coal, coal, natural gas and oil, are all resources connected to energy production. The next three columns represent actual resources included in the PV system with iron being the highest if them, followed by aluminum and copper.

The inverter and roof installation are the most demanding parts regarding the use of metals.

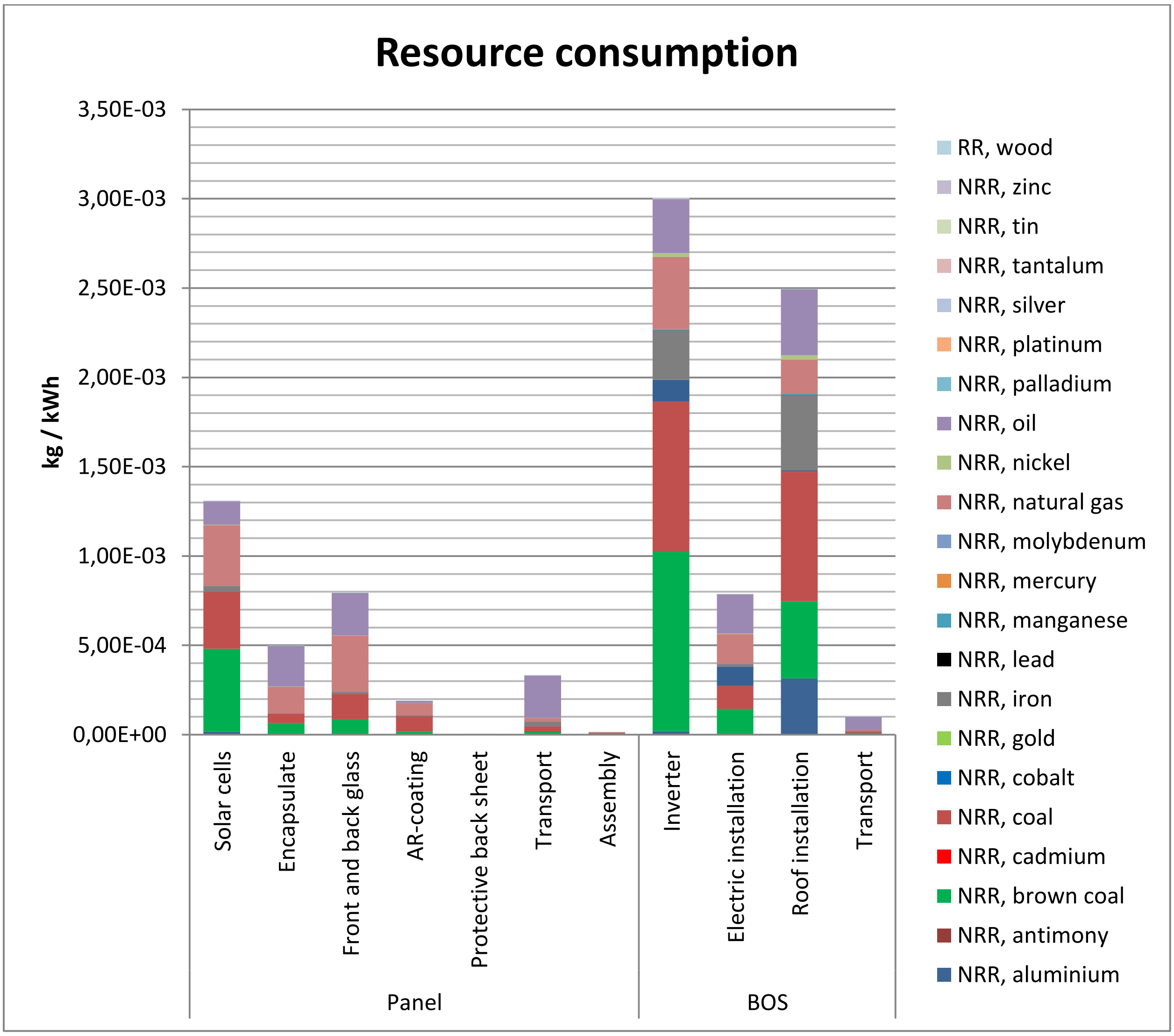

Figure 17: The same data as in Figure 16 only the x-axis is changed to enable easier comprehension of the amount of resources required per PV panel sub-product. NRR stands for non-renewable resources and RR stands for renewable resources. Each section of the columns represents the amount of resources used and does not extend down to the x-axis behind the other sections. The column sections are arranged in the same order as the presented resources on the right hand side.

Figure 17 is similar to figure 16 with the difference being that the recourses and sub-parts have changed place in order to easier identify the difference in scale between the sub-products. Here it can be clearly seen that the inverter is the most resource demanding process followed by the roof installation and solar cells. The category BOS accounts for the majority of resources in comparison to the panel.

The total final resource use is $9{,}51 \cdot 10^{-3}$ kg/kWh.

4.1.2 Land

The majority of land use is derived from the solar cell production. Two other major contributors to this impact category are roof installation and inverters but are not even close to the value for solar cells. Pay attention to the values since the x-axis in the diagram is not linear but adjusted in order to enable better oversight of the majority of the parts.

The total land use is 2,3*10^{-3} m^2a/kWh.

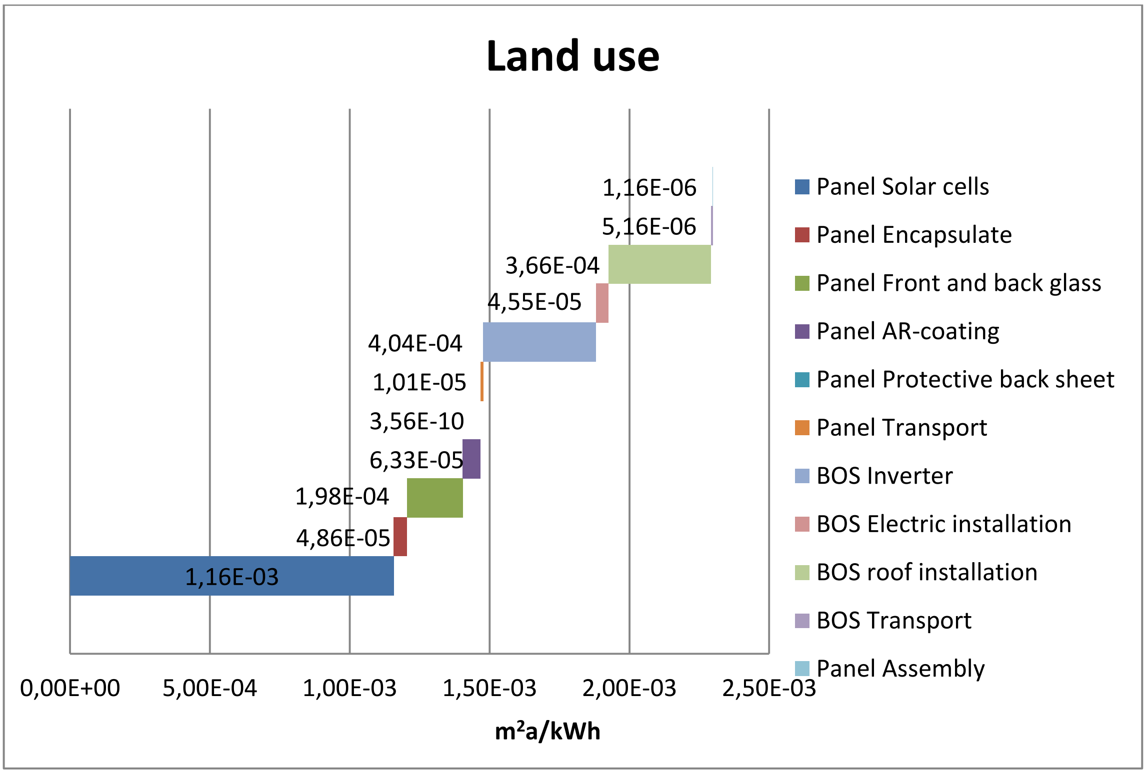

Figure 18: The figure represents the annual areal use per FU for the total 3 000 Wp PV system. The description field, on the right, represents the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.1.3 Water

The water use is dominated by the production of solar cells, followed by inverter, roof installation and glass production. The panel requires approximately double the amount of water as BOS does and the consumption is almost solely from the solar cell in the panel category.

The total amount of water use is $1{,}06 \cdot 10^{-3}$ m^3/kWh.

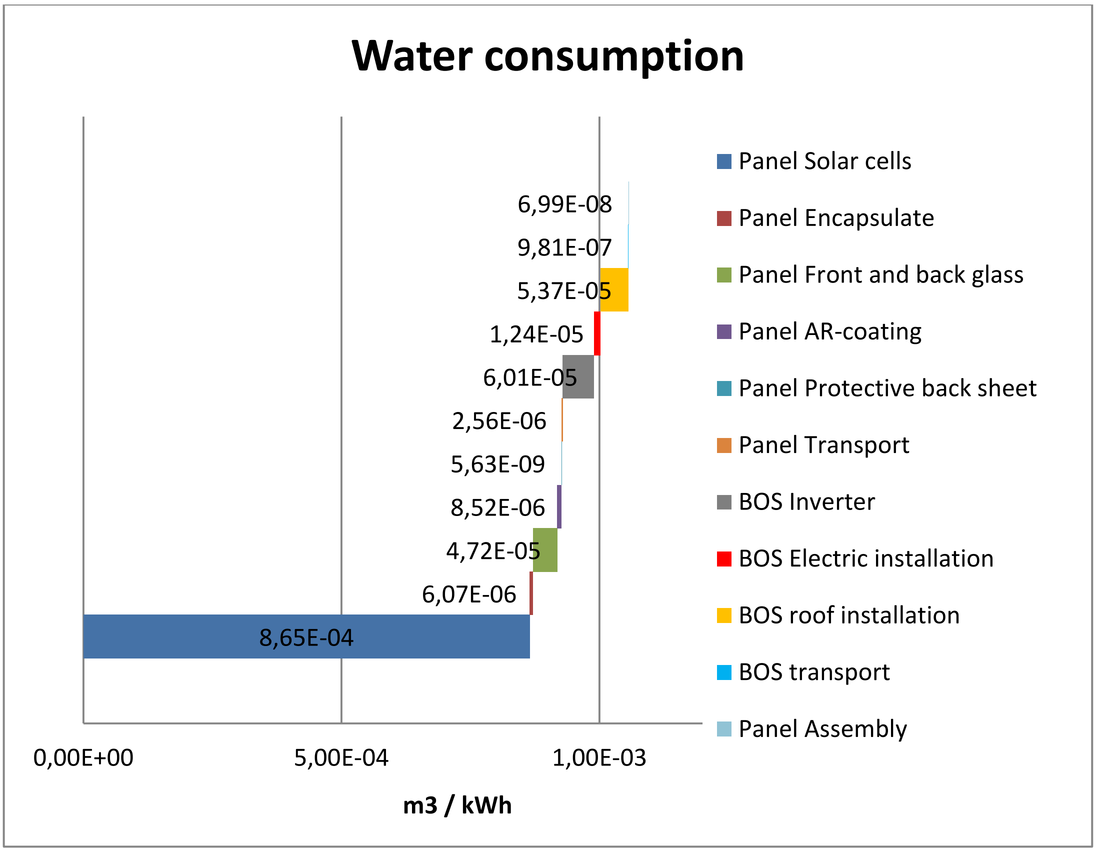

Figure 19: The figure represents the annual water use per FU for the total 3 000 Wp PV system. The description field, on the right, represents the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.1.4 Cumulative energy demand

The CED category is yet again dominated by the solar cell production and requires far more energy than all remaining parts combined. The roof installation and inverter production are the second and third energy demanding processes of the PV system. The results demonstrate how energy intensive the solar cell production is.

The total final CED for the PV system is 0,31 kWh/kWh.

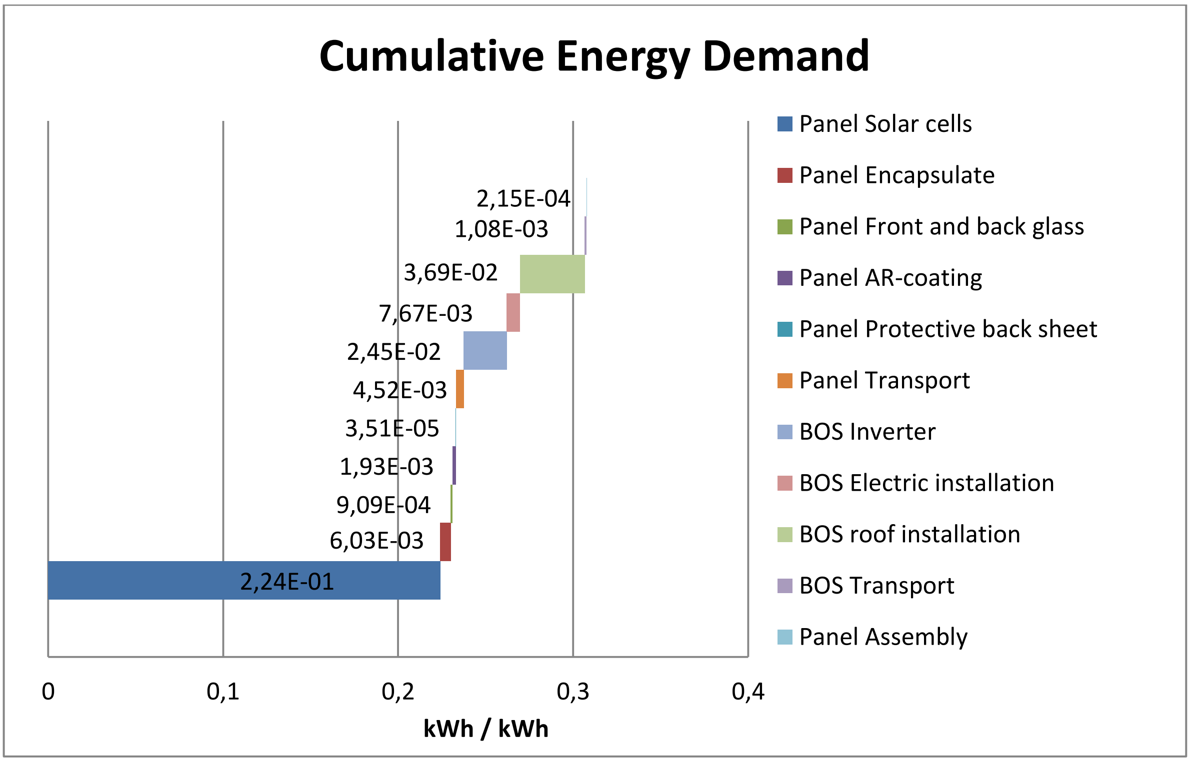

Figure 20: The figure represents the CED per function unit for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

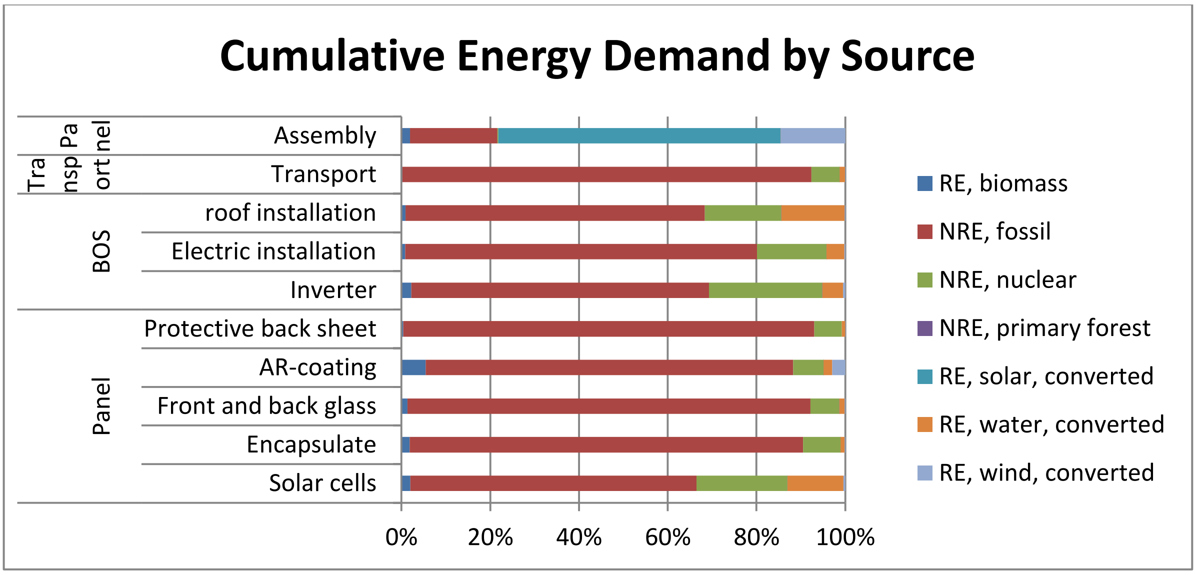

Figure 21: Cumulative energy demand per source for the parts, and transport, of the studied PV system.

4.1.5 Renewable energy

Since the renewable energy values are derived from the CED, it comes as no surprise that the solar cell production is the most energy demanding process. The majority of the renewable energy originates from hydropower. A process, along the production chain for solar cells, is located in Norway and thus the Norwegian energy mix is taken into account. See metadata in appendix 4.

The roof installation and inverter production are the second and third largest production processes using renewable energy.

The total amount of renewable energy for the production of 3 000 Wp solar system is 0,041 kWh/kWh.

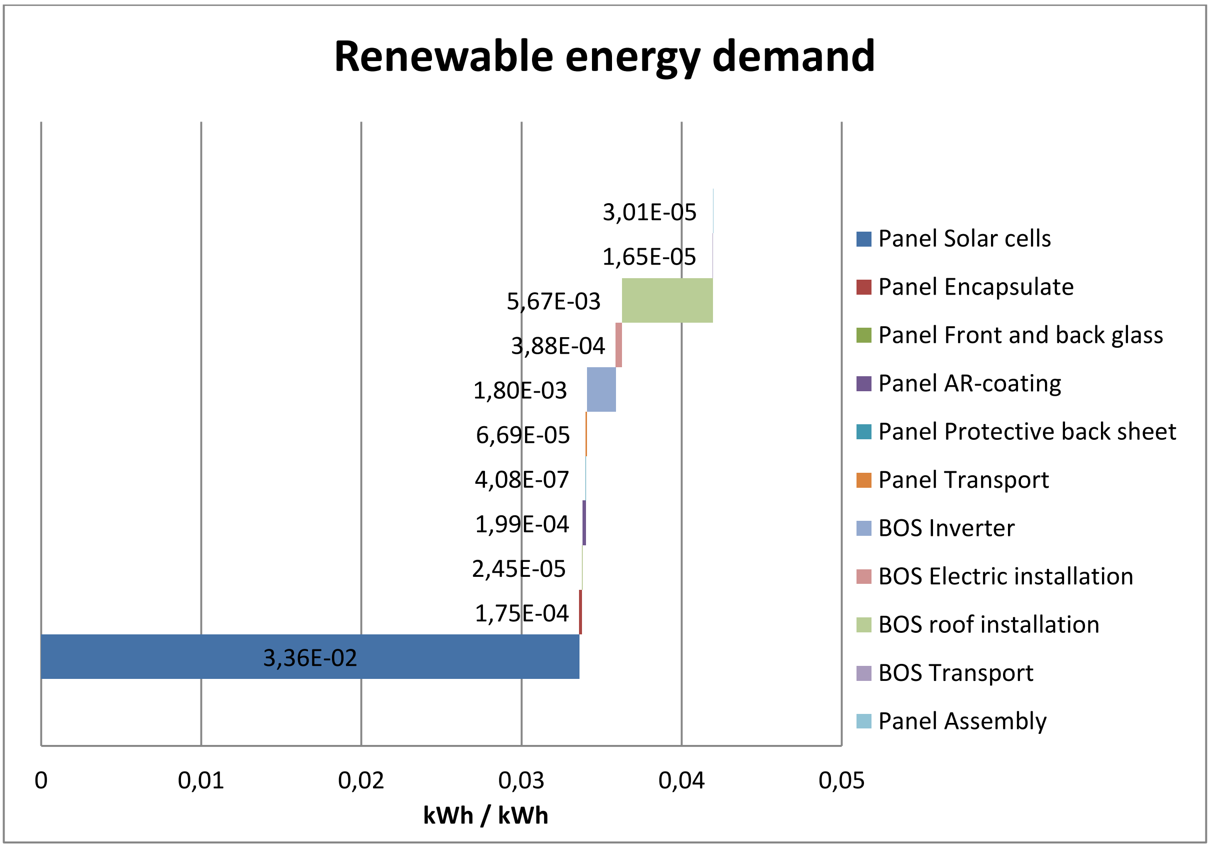

Figure 22: The figure represents the renewable energy per function unit for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.1.6 Non-renewable energy

The non-renewable energy consumption is similar in proportions to the renewable energy demand in figure 22. The difference is in the amount. The total non-renewable energy demand is 0,27 kWh/kWh. This is more than six times the amount of renewable energy used. The solar cell solely requires 0,19 kWh/kWh.

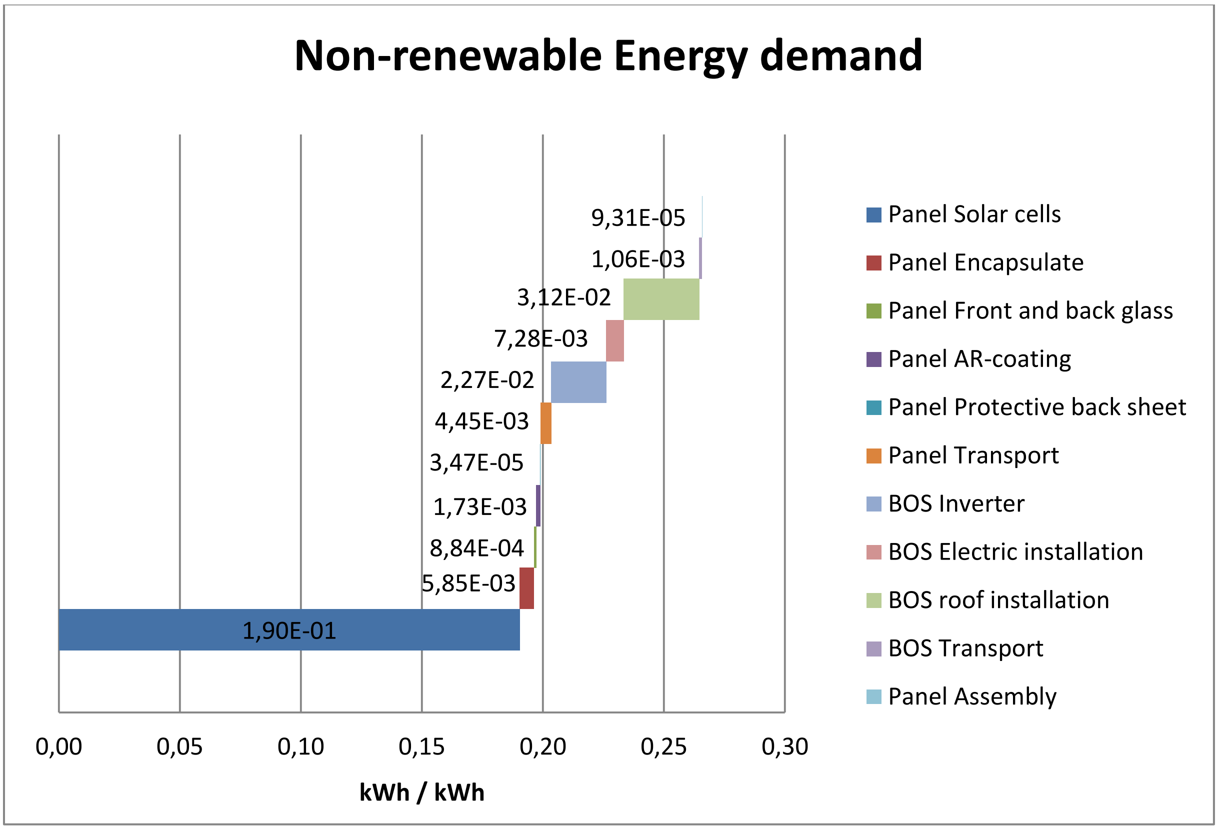

Figure 23: The figure represents the non-renewable energy per function unit for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.2 Environmental Impact

Environmental impact, in this LCA study, consists of four impact categories namely global warming potential, acidification potential, eutrophication potential and ozone depletion potential, as seen below and in section 2.8.

4.2.1 Global warming potential, 100 years

The largest potential emissions contributing to GWP originate from the solar cell production followed by roof installation and inverter. Remaining parts, included in the PV system, are not even close to the results of solar cell production.

The total global warming potential for a 3 000 Wp PV system is 0,053 kg CO_2-eq/kWh.

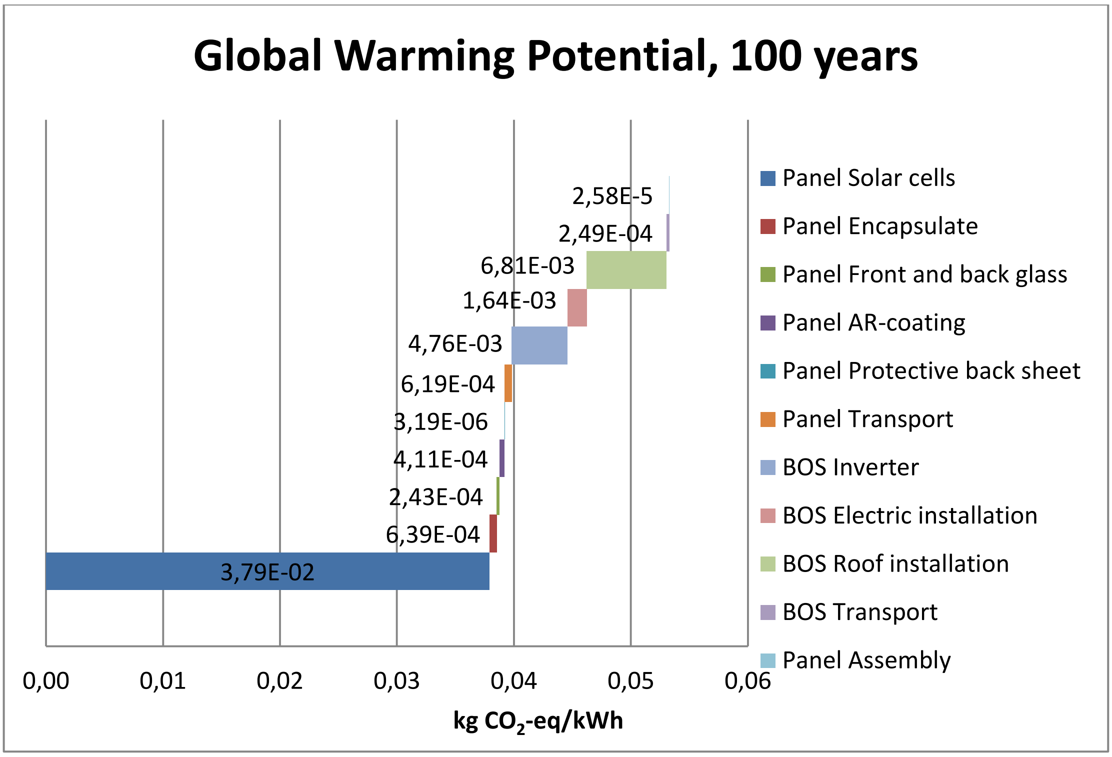

Figure 24: The figure represents the GWP per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.2.2 Acidification Potential

The highest contributor to potential acidification originated from the solar cell production. This impact category is still dominated by the cell production potential effects but not in the same extent as in previous categories. There are three other significant contributors to acidification potential namely the production of inverter, roof installation and electric installation.

The total final acidification potential is $2{,}4 \cdot 10^{-4}$ kg SO_2-eq/kWh for a 3 000 Wp PV system.

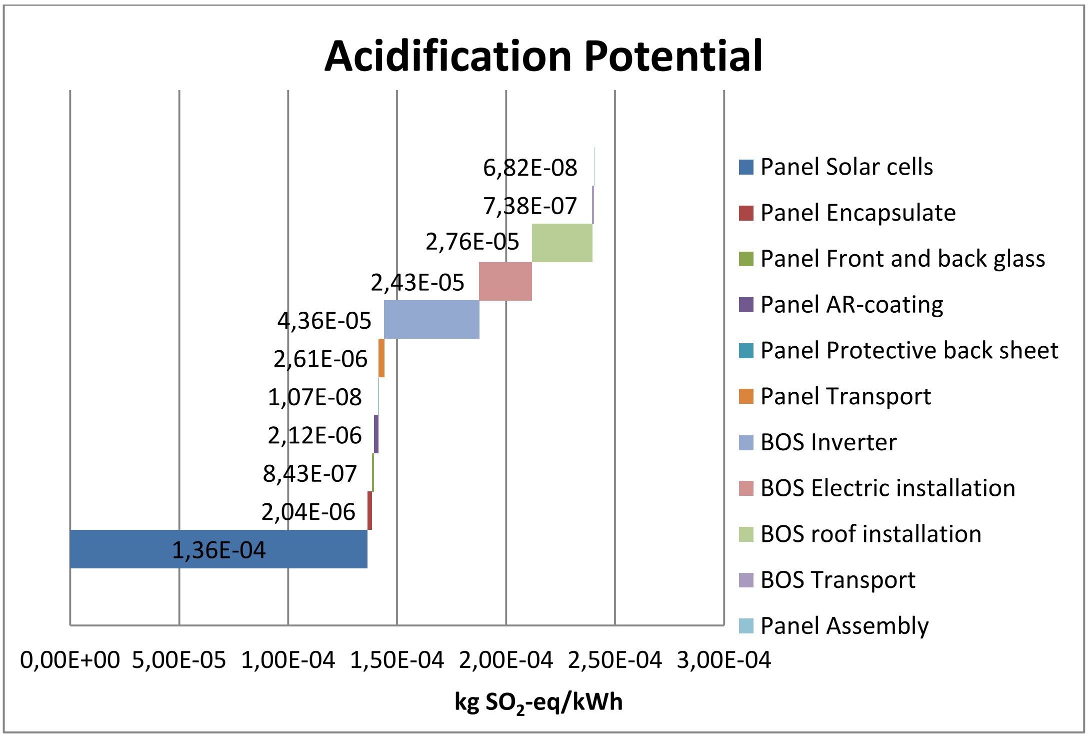

Figure 25: The figure represents the AP per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.2.3 Eutrophication Potential

The contribution to the highest eutrophication potential is due to solar cell production, followed by inverter and roof installation production. The impact from the panel and BOS are almost equal for the EP.

The total final eutrophication potential is $1{,}36*10^{-4}$ kg NO_x-eq/kWh for the studied PV system.

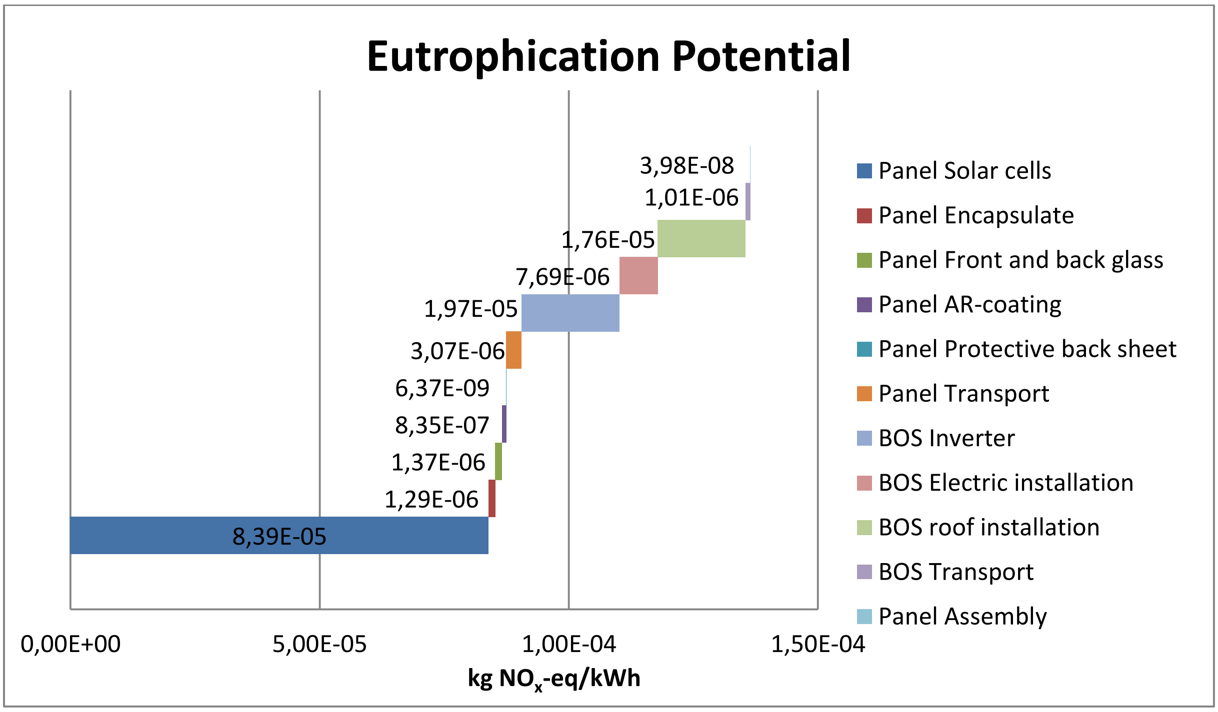

Figure 26: The figure represents the EP per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.2.4 Ozone depletion potential, 10 years

The results for ODP are overwhelmingly represented by the solar cell production. The results for solar cells alone are over 16 times greater than the remaining parts combined. The total final amount of ODP is 2,25*10^{-8} kg CFC-11- eq/kWh.

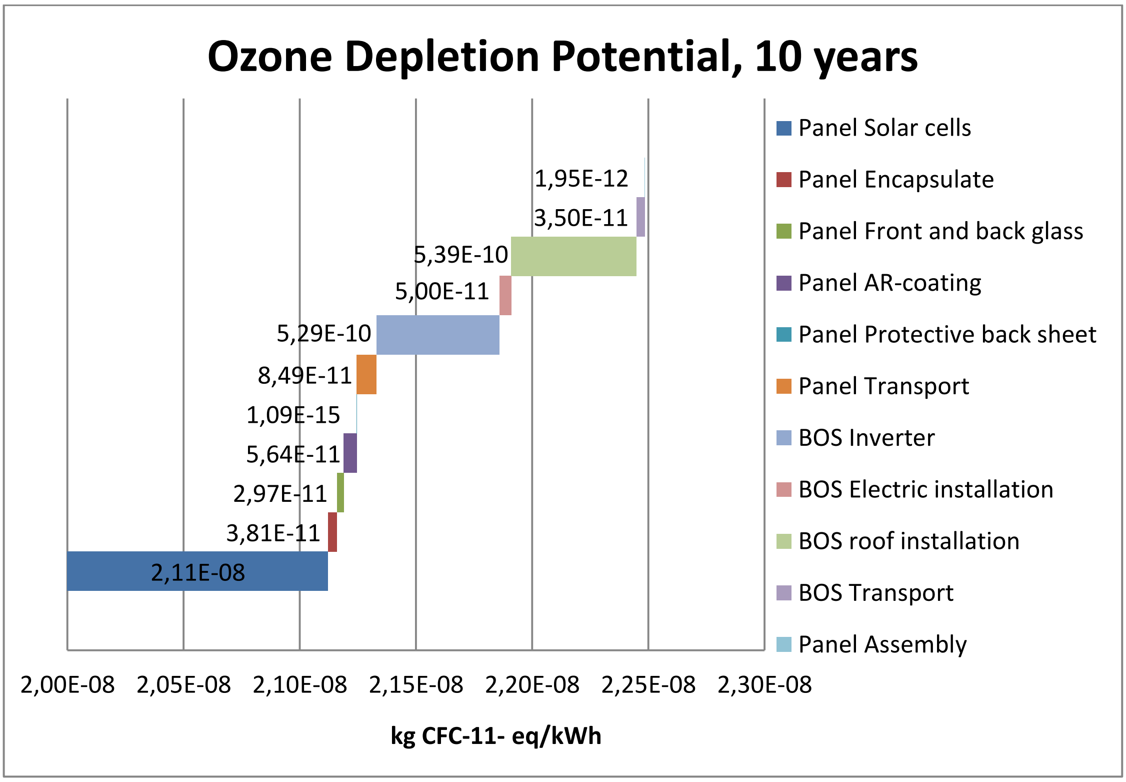

Figure 27: The figure represents the ODP per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.3 Human effect

Human effect in this study consists of two impact categories which are human toxicity, 100 years and ionizing radiation.

4.3.1 Human toxicity, 100 years

The HTP impact category is quite diverse. The highest contribution to HTP comes from the roof installation production followed by the production of the inverter, electric installation and solar cells. Almost half of the total contribution to this impact category is derived from the roof installation production process.

The total final amount of ODP is 0,086 kg 1,4-DCB-eq/kWh for the PV system.

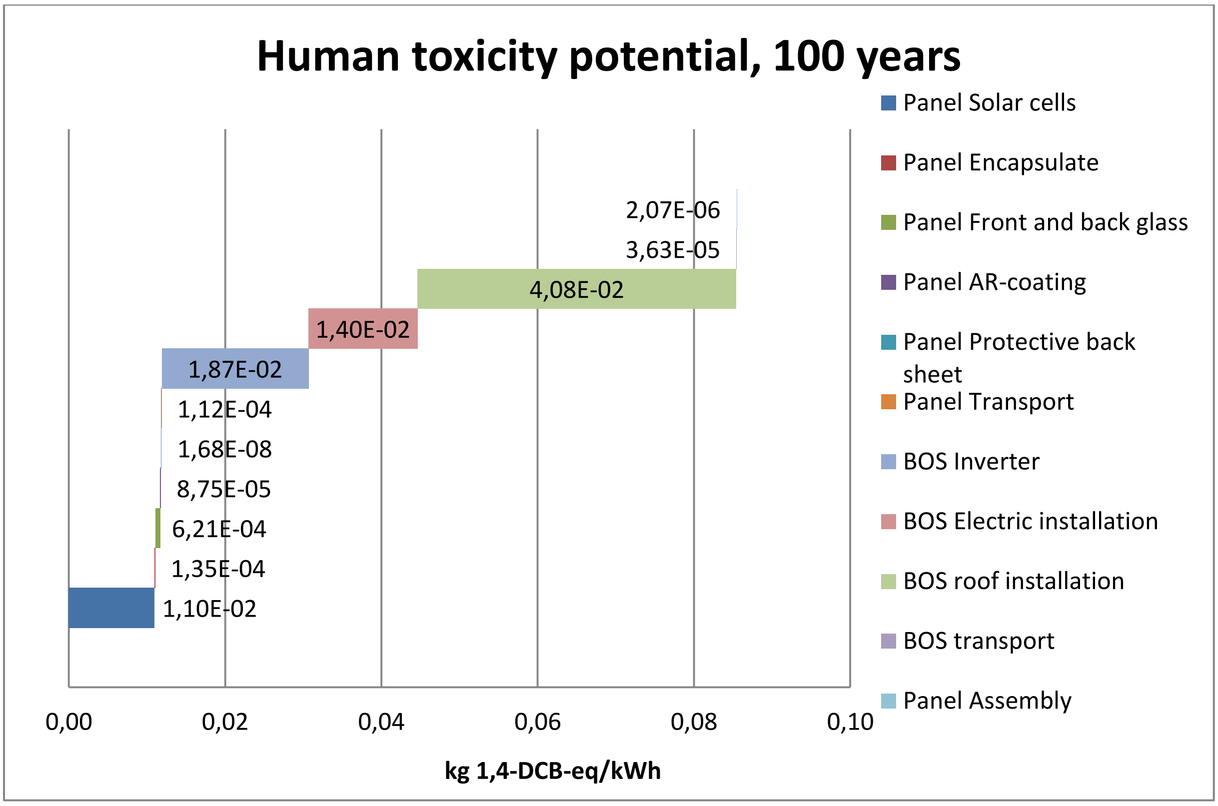

Figure 28: The figure represents the HTP per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.3.2 Ionizing radiation

The production processes of the roof installation and the inverters are the predominant contributors to the ionizing radiation, followed by the solar cell production. For this impact category, the BOS is contributing to ionizing radiation in higher degree than the solar panels.

The total final ionizing radiation is $1,5*10^{-10}$ DALY-eq/kWh for the PV system in this study.

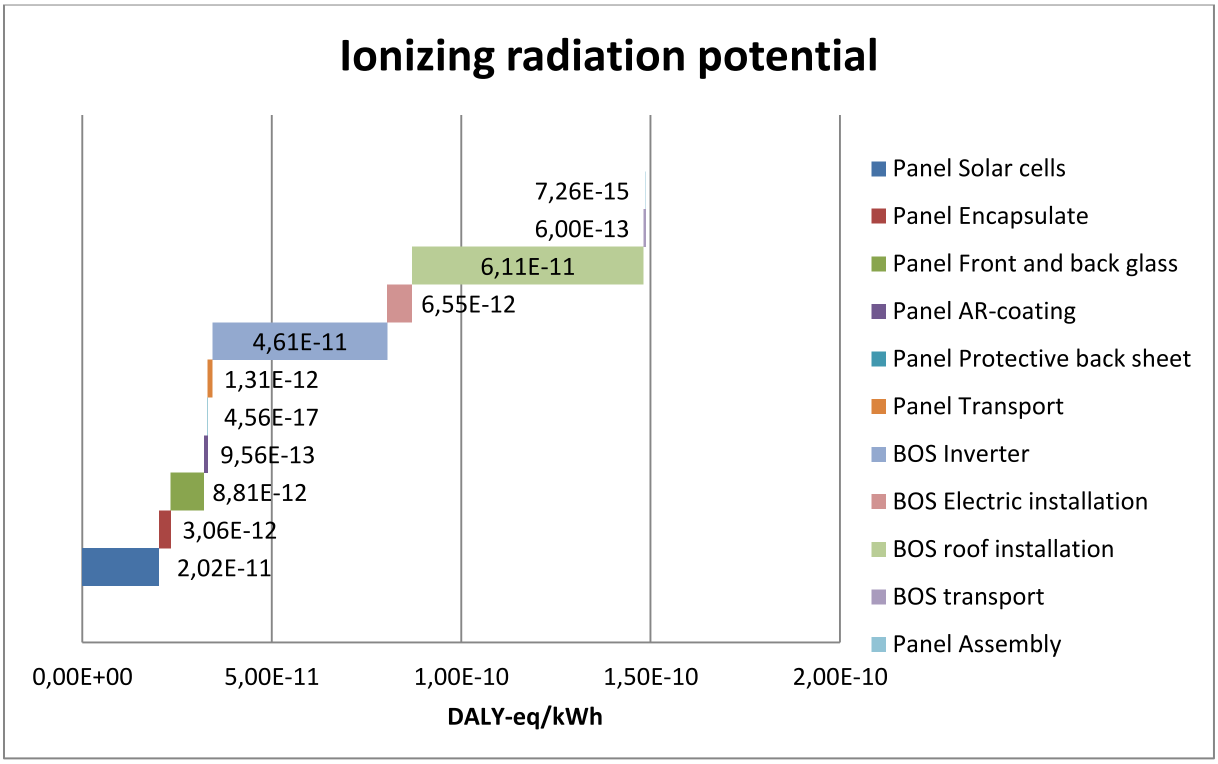

Figure 29: The figure represents the IR per FU for the total 3 000 Wp PV system. The description parameters, on the right, represent the opposite arranging of the diagram sections. Panel solar cells are at the bottom and BOS Transport is at the top.

4.4 Cumulative results

The figure below enables a total oversight of all impact categories for the studied PV system. The columns are representative for the total sum of impact categories per PV system parts in percent, not showing difference in magnitude between the parts.

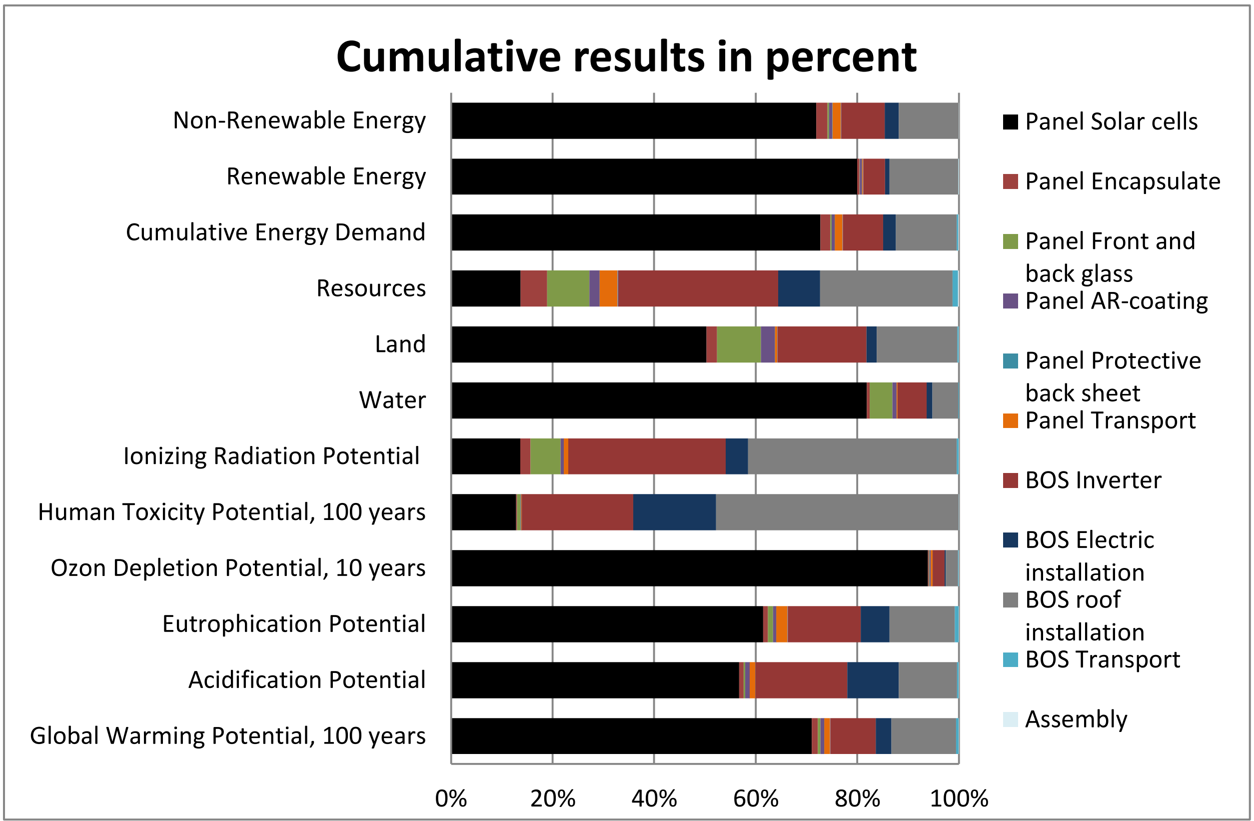

Figure 30: Cumulative impact category results for the studied PV system.

4.5 Energy Pay-back Time

Energy payback time is a measure describing the time it takes for the PV system to generate the same amount of electricity, relative to the electricity efficiency in the grid, as was needed for the production of the PV system itself[107]. One important parameter that needs to be known, in order to calculate the EPBT, is the efficiency of the grid, meaning the ration between energy input from fossil sources and the electricity output from these sources. Basically it is the electricity production efficiency of the country, assumed that no electricity imports are made.

The energy payback time formula is presented, amongst others, by IEA PVPS Task 12, *Life cycle inventories and life cycle assessment of photovoltaic systems*, and is shown below.

$$EPBT = \frac{E_{mat} E_{manuf} E_{trans} E_{inst} E_{EOL}}{((E_{agen}/\, \eta_G) - E_{aoper})} \quad (5)$$

[107] Jungbluth, N., et.al., op.cit., p. 152

Where,

E_{mat} = Primary energy demand to producing materials for the PV system

E_{manuf} = Primary energy demand to manufacture the PV system

E_{trans} = Primary energy demand to transport all resources used in the PV system

E_{inst} = Primary energy demand to install the PV system

E_{EOL} = Primary energy demand for end of life treatment

E_{agen} = Annual generated electricity

E_{aoper} = Primary energy demand for operation and maintenance

η_G = Grid efficiency, average primary energy converted into electricity in the country

Table 25: Presentation of the parameters included in the EPBT calculation.

	E_{mat}	E_{manuf}	E_{trans}	E_{inst}	E_{EOL}	E_{agen}	E_{aoper}	η_G
kWh	23329,66	10,74	502,00	0	0	2775	0	0,35

Ecoinvent data presents several of the presented parameters cumulatively. It does not separate production of materials for the PV system from manufacturing of the PV system. The only difference between these two parameters is the assembly energy demand. Therefore E_{mat} will represent the manufacturing of the PV and the producing materials as a cumulative value. E_{manuf} will on the other hand only present the assembly of the PV panels, since all other manufacturing energy demand are included in the E_{mat}. A third parameter that is also included in all parts of the PV system and cannot be separated from the Ecoinvent data is E_{EOL}. As mentioned earlier, all parts are assumed to be deposited/treated within the Ecoinvent data to some degree, but the results for just E_{EOL} are impossible to obtain from the cumulative Ecoinvent data. The E_{EOL} data is thus also included in and represented in E_{mat}. The remaining parameters are, as earlier assumed, zero.

The conversion quota between primary energy input and electricity output is 35%[108]. The total cumulative energy demand for the PV system in this study is 23 842,4 kWh and the electricity production for the first year is 2 775 kWh.

$$EPBT = \frac{23842{,}4\ kWh}{\left(\frac{2775\ kWh}{0{,}35}\right) - 0)} = 3\ years$$

The energy payback time is in this case 3 years.

[108] ABB, *Denmark Energy Efficiency Report*, 2013, retrieved 15 May 2014, <http://www05.abb.com/global/scot/scot380.nsf/veritydisplay/81ca7ecdf0764500c1257be80053b4e0/$file/Denmark.pdf>

4.6 Spared emissions in Danish electricity mix

By connecting a PV system to the grid, the solar generated electricity replaces the otherwise to be produced electricity in Denmark if no PV was installed. It spares the production of electricity from the national electricity mix. Danish electricity is produced, with 92% reliability[109], from wind generation, hydro power, thermal production form renewables and thermal production from non-renewables, and their respective annual production is 10 267 GWh, 18 GWh, 3 935 GWh and 14 700 GWh[110] as shown in figure 26.

A large amount of the total electricity production is from renewable energy sources, but still a very large section of the electricity originates from fossil fuels and emits greenhouse gases to the atmosphere. PV system generated electricity is assumed to replace the non-renewable generators only and not the renewable ones. It would be unfortunate to replace a renewable energy source while non-renewables still dominate the electricity mix, hence this assumption.

A convenient CO_2 migration table for Denmark is presented by IEA PVPS Task 10[111] in order to calculate the amount of CO_2 replacement by installation of a PV system. The presented values enable a simple calculation for the amount of saved CO_2 emissions. See the figure below.

results for Copenhagen

Copenhagen	Global horizontal irradiation 985 kWh/m2	
	Roof-top	Façade
Annual output [kWh/kWp]	850	613
Energy Pay-Back Time [years]	3,0	4,1
Energy Return Factor [number of times]	9,1	6,3
Potential for CO_2 mitigation [tCO_2/kWp]	13,7	9,9

Figure 31: The table shows the potential CO_2 migration derived from the annual output. Source: Gaiddon, B., et.al., IEA-PVPS-Task 10, 2006, Compared assessment of selected environmental indicators of photovoltaic electricity in OECD countries, p. 23

109 Energinet.dk, *Environmental key figures for electricity*, 2013, retrieved 15 May 2014, <https://www.energinet.dk/EN/KLIMA-OG-MILJOE/Sider/Environmental-key-figures-for-electricity.aspx>
110 ibid.
111 Gaiddon, B., et.al., IEA-PVPS-Task 10, 2006, *Compared assessment of selected environmental indicators of photovoltaic electricity in OECD countries*, p. 23

The potential for CO_2 migration is presented in the lower left table and corresponds to 13 700 kg CO_2/kWp installed. The value is based on a lower annual output than the one used in this study (925 kWh/kWp) and after a simple conversion, the new, more representative value for the CO_2 migration results in 14 900 kg CO_2/kWp.

When multiplied with the total amount of installed power, which is 3 kWp, the speared CO_2 emissions result in approximately 44 700 kg CO_2.

In order to confirm this value, an alternative calculation was conducted based Danish electricity data provided by eneginet.dk. The following tables present the values of importance for conduction a CO_2 migration calculation.

Table 26: Specific electricity generation in Denmark, in GWh. Source: Energinet.dk, Environmental key figures for electricity, 2013

Specification of electricity generation	**GWh**
Electricity from wind turbines	10 263
Electricity from hydropower and photovoltaics	18
Electricity from thermal production on RE-fuels	3 935
Electricity from thermal production on non-RE fuels	14 700

Table 27: Environmental impact gases emission from electricity generation in Denmark, in tons. Source: Energinet.dk, Environmental key figures for electricity, 2013

Emissions		
Carbon dioxide (CO_2)	Tonnes	14 076 363

The following formula was put together in order to enable the CO_2 migration.

$$CO_2\,migration = \left(\frac{CO_2\,emissions - \left(\frac{(thermal\,electricity, renewable)}{(thermal\,electricity, non - renewable)} *\ CO_2\,emissions\right)}{thermal\,electricity, non\,renewables * 1\,000\,000\,kWh/GWh}\right) * 77\,486{,}77\,kWh * 1000\frac{kg}{ton} = 54\,000\,kg\,CO_2 \quad (6)$$

The CO_2 migration results in 54 000 kg CO_2 which is somewhat close to the previous result and the difference is due to ruff assumptions made in the calculation and probably different data compared to previous calculations. The electricity mix is also assumed to be fixed, representative for today, during the next 30 years which correspond to the lifetime of the PV system.

Nevertheless, the calculation roughly confirms the validity of the first calculation. Therefore the final CO_2 migration, due to the installation of 3 kWp PV system in Denmark, is 44 700 kg CO_2 throughout the lifetime of the PV system.

4.7 Extended PV system lifetime to 40 years

If the lifetime of the PV system endures 40 years, there will logically be additional electricity production compared to a 30 years lifetime. The total electricity output will thus be higher and because the electricity generation is directly connected to the function unit, all impact category results will in turn be divided by the 40 year electricity production. The 40 years case will result in a lowering of all impact category results presented.

The electricity output for 30 and 40 years of lifetime for the PV system, result is 77 486,77 kWh and 100 832,33 kWh respectively. The quota between these values is 0,77 which means that all results will be reduced by 23% if the PV system endures 40 years compared to 30 years. This applies to all results presented in previous sections.

The reason that the resulting reduction of the results is not 25 %, as is reasonable when the lifetime increase is ¼ of 40, is due to the yearly degradation of the system and thus lower electricity generation per year.

The results for the two cases, 30 and 40 years, are presented below. In order to comprehend the units of the impact categories, see the results from figure 16 to 29.

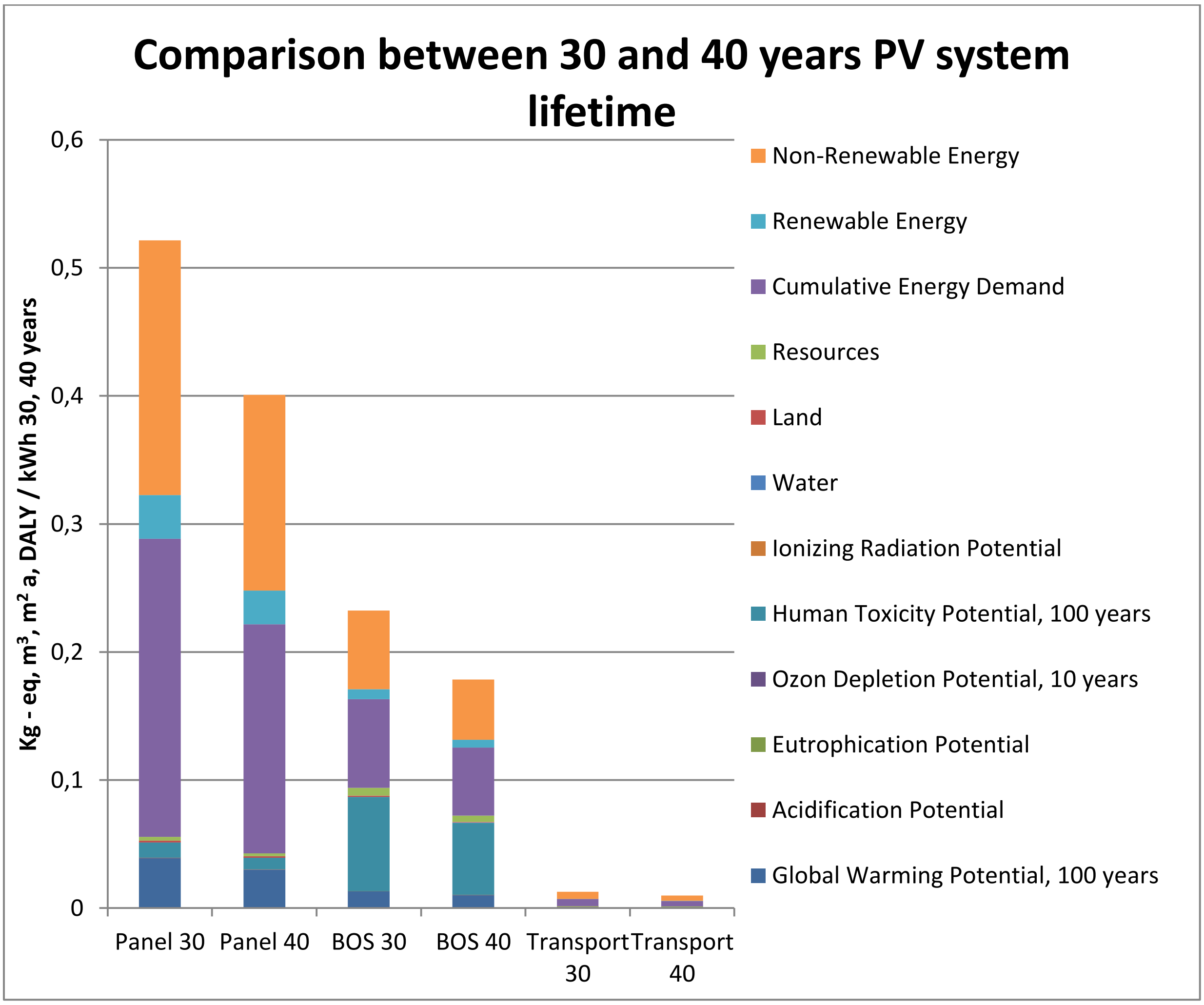

Figure 32: Impact categories results for Panel, BOS and transport for 30 and 40 years lifetime PV system. The units for the impact categories differ, hence the presentation choice for the y-axis.

An increased lifetime of the PV system will also increase the CO_2 migration with 13 410 kg CO_2 resulting in a total of 58 110 kg CO_2 migration. The values are obtained in the same way as for the 30 years case in the previous section.

5 Interpretation and Discussion

This section includes interpretation of the result, description of the origins and effects of the different impact categories. An improvement section is included for the reduction of the solar cell thickness from 270 μm, included in this study and based on Ecoinvent data, to 180 μm which is the actual thickness of the solar cells used by Gaia Solar.

5.1 Technology improvement

As seen in the results, solar cells accounted for the largest impacts in almost all categories despite their low weight in comparison to the remaining parts of the PV system. This indicates that the solar cell production is a very intensive and energy demanding process. As mentioned earlier and as seen in appendix 4, almost all data for the processes of the solar cell, are obtained in 2005-2006. This is quite an unaccounted for gap in technology evolution and production efficiency. More recent reports from 2009 suggest that the solar cell technology has improved in all fields, such as irradiation conversion efficiency, material saving and manufacturing efficiency[112]. One of these improvement steps is the reduction of solar cell thickness from 270 μm, as used in this study, to 180 μm which is the actual thickness of the solar cells used by Gaia Solar[113]. The reduction in thickness results is 33% material savings and all solar cell production stages, up to the wafer sawing, are effected by such a change. The remaining stages treat the solar cell surface and are not affected by the reduction in solar cell thickness.

Table 28: Cumulative Energy Demand (CED) for each process of the solar cell production for a 3 000 Wp PV system. It is not presented per FU. The sum of all processes up to wafer sawing are presented as well as the sum remaining processes. Further information per FU can be found in Appendix 5.

(kWh)	Sand	MG-silicon	SoG-silicon	Si-production mix	CZ Si-silicon	Wafer sawing	Cell production	Met. Paste front	Met. Paste back	Met. Paste alum.
CED (kWh)	1,7	711,3	4126,4	484,0	6085,6	2835	2986,1	46,5	24,0	62,4
SUM (kWh)					11409					5954

The table above presents the cumulative energy demand (CED) from the production of solar cells. The formula below is intended to recalculate the energy reduction by reducing the thickness of the solar cell up to the wafer sawing process.

$$New\ CED = \left(\sum sand\ to\ CZ\ Si\ silocon\right) * (1 - 0{,}33) + \sum wafer\ sawing\ to\ met.paste\ alum. \qquad (7)$$

$$New\ CED = (11409) * (0{,}66) + 5954 = 13\ 484\ \text{kWh}$$

112 Fthenakis, V. et. al., IEA – PVPS – Task 12, *Life cycle inventories and life cycle assessment for photovoltaic systems*, p. 7

113 Sunrise, *monocrystalline solar cells, 3 bus*, 2012, retrieved 15 May 2014, <http://www.sunriseglobalsolar.com/document/mono3bb.pdf>

$$Reduction\ (\%) = 1 - \frac{New\ CED}{Old\ CED} * 100 \qquad (8)$$

$$Reduction\ (\%) = 1 - \frac{13\ 484\ kWh}{17\ 363\ kWh} = 0{,}223 = 22{,}3\%$$

The new CED is reduced by 22,3% to 13 484 kWh. This is a major reduction for the CED of solar cells, from a previous value of 17 363 kWh, and for the whole PV system as well. Similar calculation was conducted for the case of the whole PV system, resulting in 16,3% reduction from 23 842,4 kWh to 19 963,4 kWh. This decrease in the total primary energy demand for the production of a 3 000 Wp PV system reduces the energy payback time from 3 years to 2,5 years, trough same methodological calculations as in previous section.

Extensive calculations were made on all sub-units, for all impact categories for the case where the cell thickness is reduced to 180 µm. The results are presented in the figure below where the data for the thinner cells are denoted with "new". Obviously there is no change in the BOS and transport since they are not affected by the reduction in cell thickness. Weight reduction for transportation of the thinner solar cells is not assumed and is the same as for the ordinary solar cells. The difference between the "sum" columns represents the difference in total impact between the case with thinner and thicker solar cells, relative to the whole PV system.

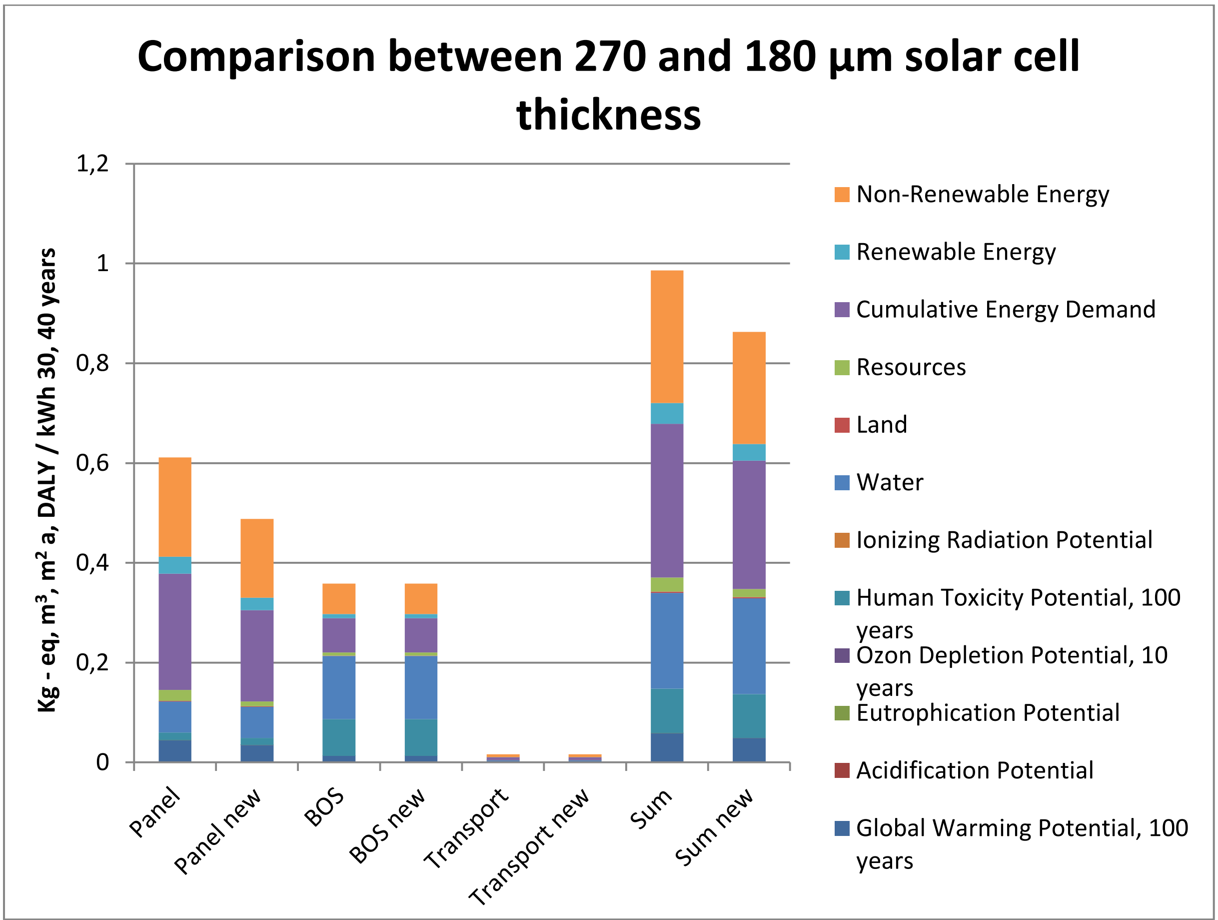

Figure 33: Change in final results due to solar cell thickness reduction per FU.

The figure below is related to figure 33 but presents only the reduction of the different impact categories due to solar cell thickness reduction. The reduction in energy was presented above but is is also of great importance to present the reduction of all impact categories. Figure 34 generally makes it easier to comprehend the reduction between the small sections in the columns in figure 33. The reduction results correspond to the reduction of the whole PV system and not just the solar cells. Results for reduction in percent can be applied on the total final results for the impact categories of the total PV system presented from figure 18 to figure 29. This simplifies the interpretation of the results compared to the results in figure 33 which are intended as an overlook comparison.

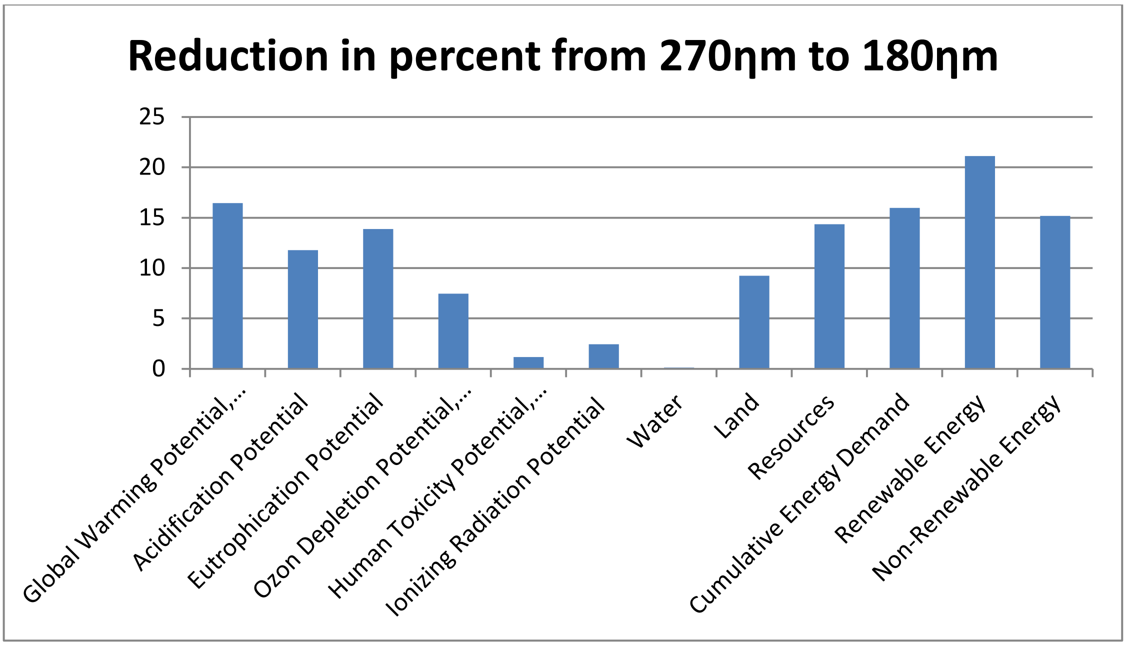

Figure 34: Reduction in percentage for the studied PV system due to reduction of solar cell thickness from 270 to 180.

5.2 Resources

5.2.1 Resource consumption

Resource consumption in this LCA is obtained through the characterization method EDIP. It includes 21 different types of resources, of estimated scarcer existence, and not resources such as sand and common minerals. The resource horizon, meaning the amount of years before a reservoir is depleted with current extraction pace, are of great importance for the characterization factor of a resource. Of these 21 resources, only one is renewable and that is wood as seen in the resource diagrams.

The reason that solar cells do not dominate the “energy resources” as seen in CED results, is that the production process of solar cells is largely derived from energy sources such as nuclear, primary forest and hydropower. These sources are not and mustn’t be represented in resource consumption since the sources are not consumed, except for nuclear power. All of these mentioned sources, except nuclear, are driven by the sun and, even biomass which due to its fast lifecycle, compared to fossil resources, is considered a renewable. These sources would be included in resource consumption if the sun’s fuel was regarded as a resource

The two most resource demanding parts, roof installation and inverters, differ much in the way they are produced and it is somewhat noticeable. They both use large amounts of fossil resources, where the inverter requires more than the roof installation, but the roof installation on the other hand consists of more metal resources. The inverter is thus more energy resource intensive, though not by much, while the roof installation requires more metal resources for construction. The weights are also a factor and while the two inverters whey slightly less than 40 kg, the roof installation is slightly above 70 kg. The solar cells also require a lot of resources compared to the total weight of the 270 μm thick solar cells, which whey slightly above 8 kg.

The inverter and roof installations, falling under the category of BOS, result in an even greater difference between resource consumption for BOS compared to the panels.

5.2.2 Water

Water use is the amount of extracted water from a lake, river, well, sea or ocean required to produce a product or service. It does not include water for cooling or energy production in hydro plants[114]. Water categorized by Selected LCI results additional, is only presented in quantitative measure of m^3 regardless of location, importance or source[115].

Water is very scarce in some places[116], especially Africa and Asia, and is an important impact category to include in LCA for processes in these regions. It is debated if water use is a more important category then global warming potential due to the amount of people affected by lack of clean drinkable water. Water may soon be presented in an own larger category, namely water footprint, including more advanced aspects and weighing methods for importance of water at different regions. A desiccation of water may also be needed in order to include the effect on the environment due to water shortage caused by agricultural, industrial and drinking demands. Desiccation is not yet implemented and incorporated into a life cycle impact category such as GWP, ODP, HTP etc. and thus the importance and impact of water cannot be assessed properly[117].

Water is mostly used for agricultural purposes[118] and therefore products related to agriculture will have higher water use, and even theoretical desiccation depending on the location, then the production of solar cells.

The production of solar cells require the most amount of water and the process sub-process of CZ-silicon cells is in turn, by far, the most water intensive one compared to the remaining solar cell production stages. See table 77 in Appendix 5 for information. This process location for the CZ-silicon stage is located in Western Europe where water is not that scarce. Solar cell production requires 82% of the water use for the total PV system.

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[114] Hischier, R., et.al., *Ecoinvent, implementation of life cycle impact assessment method*, report no. 3, 2010, retieved 15 May -14, <http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation-v2.2.pdf>, p. 162
[115] Budavari, Z., et.al., *LoRe-LCA, low resource consumption buildings and constructions by use of LCA in design and decision making*, 2011, retrieved 15 May 2014, <http://www.sintef.no/project/LoRe-LCA/Deliverables/LoRE-LCA-WP5-D5.1-EMI_Final.pdf>
[116] Pfister, S., *Water resource in LCA, existing methods, regionalized aspects and future development*, ETH Zurich, 2010, retrieved 15 May 2014, <http://formations.cirad.fr/analyse-cycle-de-vie/pdf/StephanPfister.pdf>
[117] ibid.
[118] UNEP, *Water scarcity index*, 2006, retrieved 15 May 2014, <http://www.unep.org/dewa/vitalwater/article77.html>

5.2.3 Land

Land use in CML 2001 characterization method accounts only for the land above water[119]. The impact is on the diversity of flora and fauna due to land occupancy. Buildings, farms, roads etc. occupy and replace a natural environment that is no more, thus affecting the biodiversity in that location[120]. The size and location of the occupied land is important because the impact is measured in loss of biodiversity, compared to unused surroundings[121]. A factory, base or cultivation located in a desert should not result in as high results for the same areal used in a highly biodiversity environments such as the rainforest.

Solar cell production showed the highest results for land use. It is unclear if the land use is related to factories land occupancy or excavation site for raw materials. It is most probable a combination of both, but to what ratio is unclear.

5.2.4 Cumulative energy demand (CED)

Cumulative energy demand represents the total primary energy demand for a product/service during the whole lifecycle. Energy is required from extraction of raw material to refining, from processing to operation and recycling etc. There are some different approximations that can be made regarding the primary energy demand. For instance there is a choice to be made regarding the heating value for fuels, the upper and the lower. The upper heating value includes evaporation of water from fuels while the lower does not, leading to different results. Generally, the majority of energy sources are considered with upper heating value but it is more complicated when it comes to nuclear power and wind, water and solar power. Due to extensive information regarding this subject and the process of determining the caloric values, the reader is referred to the Ecoinvent report[122].

Ecoinvent data on CED consists of 7 different primary energy sources, 4 renewable and 3 fossil.

The cumulative energy demand for the production of solar cells reflects on the energy intensity of the production process. Approximately 73% of the total CED is used in the solar cell production processes. This has nothing to very little to do with the mass of the solar cells. The whole PV system is assumed to be slightly lower than 500 kg and the solar cells are around 8,5 kg. Still, the solar cell production process requires 73% of the total energy for the PV system.

If the solar cell production wore produced by the MG-silicon and EG-silicon pathway presented in figure 7 & 8, the percentage would be even greater.

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[119] Hischier, R., et.al., op.cit., p. 29
[120] Goedkopp, M., et.al., *SimaPro database manual, method library*, report no. 2, 2008, retrieved 15 May 2014, <http://www.pre-sustainability.com/download/manuals/DatabaseManualMethods.pdf>
[121] Baumann, H., et.al., op.cit., p. 148
[122] Hischier, R., et.al., *Ecoinvent, implementation of life cycle impact assessment method*, report no. 3, 2010, retieved 15 May -14, <http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation-v2.2.pdf>, chap. 2

5.2.5 Renewable energy

The renewable sources presented in this study are biomass, water (hydropower), wind (wind turbines) and solar (PV systems). It can be unclear, for some, what biomass includes while the remaining are obvious. Biomass includes sources such as wood, food products, agricultural biomass[123].

Solar cell production also required the most of the total renewable energy for the PV system. Around 80% of the total results are represented by the production of solar cells. Hydropower accounted for 85% of the total renewable energy demand for the production of solar cells. The total renewable energy use for the whole system was only 13,5% of the total CED.

5.2.6 Non-renewable energy

The non-renewable energy resources are fossil, nuclear and primary forest. The fossil fuels are hard coal, peat, crude oil, lignite and natural gas.

The non-renewable energy category is predominantly represented by the use of fossil fuels. Yet again, in consistency with the CED and renewable energy, the solar cell production process accounted for the majority of the non-renewable energy demand.

5.3 Environmental impact

5.3.1 Global warming potential

Global warming potential and the term often used, with somewhat misleading name, carbon footprint, are usually the categories of interest for presentation of a products/service environmental impact. The term carbon footprint is not used in this study and instead global warming potential is used. Carbon footprint has the same definition as global warming potential[124] but could be interpreted, by the name, as if it only accounts for the carbon dioxide emissions and not the remaining greenhouse gases.

It could be speculated why global warming potential is the category of choice when presenting impacts of products. It could be due to the intensified global warming discussion and political rhetoric about global warming and carbon emission, but one must not forget that other impact categories are of high importance as well. A low global warming potential of a product does not mean low human toxicity potential, low acidification potential etc. Therefore it is of great importance to include as many categories as possible in order to present the products effect on a wider impact spectrum.

There are many substances that have a global warming effect but the most common are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (f-gases, HFC, PFC, SF_6)[125]. The presence of these gases in the atmosphere enable incoming solar energy, in form of short wave solar irradiation, to pass through in higher rate than the earth's long wave radiation (infrared, heat) emits

[123] ibid., p. 34
[124] Baldwin, S., *Carbon footprint of electricity generation,* Parliamentary office of science and technology, retrieved 14 May 2014, <http://www.geni.org/globalenergy/library/technical-articles/carbon-capture/parliamentary-office-of-science-and-technology/carbon-footprint-of-electricity-generation/file_9270.pdf>
[125] EPA, *global greenhouse gas emissions data*, 2013, retrieved 15 May 2014, <http://www.epa.gov/climatechange/ghgemissions/global.html>

energy from the earth. The physiological properties of the gases enable the gases to absorb the radiation from earth by exiting the electrons to a higher electron orbit, thereafter spreading it again after the exited electrons fall back into the original orbit. It could be said that 50% of the reemitted energy from the atmosphere is spread up into the universe and 50% back to earth[126].

The emitted greenhouse gases to the atmosphere are not only accumulated but there are also reduced by natural sinks such as deposition in the oceans, uptake by algae, uptake by terrestrial vegetation and chemical reactions in the atmosphere[127]. Despite that, the concentration of CO_2 in the atmosphere increases by 1,8 ppmv/year[128] (parts per million by volume/year) and is approximately 400 ppm in 2014[129]. Anthropogenic sources for the increase of greenhouse gases are energy plants, industry, land use and forestry, transportation and more[130] while natural sources are volcanoes, soil erosion in the lithosphere, gas-water exchange of the hydrosphere etc[131]. According to IPCC, the increase is due to anthropogenic activity. Most of the anthropogenic emissions are due to combustion of fossil fuels as seen on the figure below.

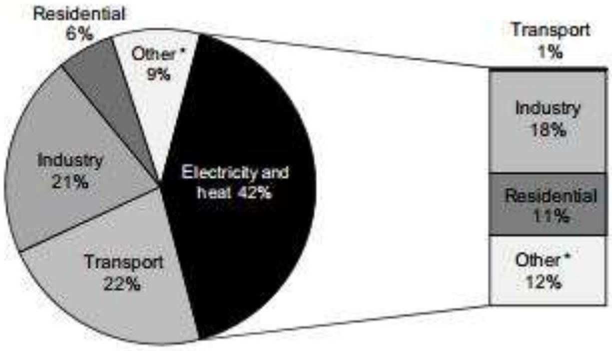

Figure 35: World CO2 emissions by sector in 2011. source: IEA, CO2 emissions from fuels, http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf

As noted in the figure above, a large portion of the emissions originate from the electricity and energy sector. Fossil fuel consuming energy generation pants contribute to increased global warming potential in the construction phase, operation phase by burning fuels, and the disposal phase. Solar energy on the other hand only contributes to emission in the production and disposal stage, thus generating electricity without contributing to global warming. There is great room and potential to replace fossil fuel with renewable sources, solar power being one of them.

It is quite reasonable that solar cell production contributes the most to GWP based on the results of the CED and especially non-renewable energy. As seen in figure 34, a whole 42% of the anthropogenic CO^2 emissions in the world originate from the heat and electricity production. The total final CO_2 emissions for the production of the PV system in this study, during 30 years, are 0,053 kg CO_2 – eq/kWh. The results are controlled against the report from *Fthenakis, V., et.al.,* and seem to be correct in comparison. The mentioned report resulted in a total of 38 g CO_2 – eq/kWh but for conditions in

[126] Jacobs, D.J., *Introduction to atmospheric chemistry,* 1999, p 129.
[127] ibid., chapter 10, chapter 6.5.
[128] ibid., p. 97
[129] Atmospheric CO_2, *Mauna Loa Observatory*, 2014, retrieved 15 May 2014, <http://co2now.org/images/stories/data/co2-atmospheric-mlo-monthly-scripps.pdf>
[130] EPA, *global greenhouse gas emissions data,* 2013, retrieved 15 May 2014, <http://www.epa.gov/climatechange/ghgemissions/global.html>
[131] Jacobs, D.J., op.cit., p. 88

southern Europe. The solar irradiation was 1700 kWh/m^2/years instead of 1150 kWh/m^2/years as for this study. Higher irradiation in turn leads to higher electricity generation and thus higher FU and in turn results in lower GWP results. This is confirmed by the EPBT of that report which resulted in 2,3 years.

The solar cell production contributes to 71% of the total GWP results for the studied PV system. This value would be lower for the actual case, with 180 μm thick solar cells.

5.3.2 Acidification potential

An acid is a proton donator, and thereby acidification occurs when a molecule donates a hydrogen, H^+ ion, to a receiving medium[132]. An increase of the hydrogen ion concentration lowers the pH of the medium and affects the biosphere. Different substances contribute to acidification with different magnitude depending on the ability of the substance to donate hydrogen ions. Fortunately there are bases which neutralize the acidity. If acid rain, for instance, falls in the ocean or in an environment with natural base resources such as limestone, the acid rain will not affect the biosphere because of fast neutralization[133]. Unfortunately emissions to air and water from anthropogenic activity in areas which lack natural bases and buffers, lead to an acidification of the biosphere.

Major acidification chemical are SO_2, NO_x, HCL and NH_3. SO_2 and NO_x are emitted from combustion of fossil fuels which in turn contribute to acidification.

In LCA, the acidification potential characterization is based on the amount of hydrogen ions produced per kg of chemical related to SO_2. As in the case for global warming potential, the acidification potential includes both stronger and weaker acids then SO_2, but they are weighed against the acidification potential of SO_2 which is the representative substance.

The contribution to the acidification is with highest probability due to fuel combustion for power generation required for the production of the PV system. The majority of the energy is utilized in the solar cell production and they consequently contribute to the highest acidification potential. The total potential acidification of solar cells is 57% of the total potential acidification from the whole PV system.

5.3.3 Eutrophication potential

Eutrophication is also referred to as nitrification[134] and describes the amount nutrients added to the ecosystem. Additional nutrients are often introduced in form of manure and fertilizers with intention to increase production form cultivated land[135]. Increased levels of eutrophication have an impact on the biodiversity by the faster growing organisms outsourcing the less abled ones. Eventually the nutrients reach a water source such as a lake, pond and the sea, and have the same effect on the aquatic life as on the terrestrial, leading to high concentration of algae at the expense of other aquatic organisms[136].

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[132] Jacobs, D.J., Chapter 13
[133] Baumann, H., et.al., p. 155
[134] ibid., p. 155
[135] European commission, *LCA, Eutrophication*, retrieved 15 May 2014, <http://qpc.adm.slu.se/7_LCA/page_09.htm>
[136] ibid.

For instance, the aerobe decomposition of the algae depletes the oxygen concentration of the aquatic environment, effecting organisms with high oxygen demand.

Substances consisting of nitrogen (N) and phosphorous (P) such as ammonia (NH_3), nitrate (NO_3) and phosphate (PO_4^{3-}) are the major contributors to eutrophication[137]. The representative substance for the eutrophication category is NO_x and other substances are converted into NO_x-equivalents the same way global warming and acidification potential substances were converted.

It is expected that products associated with cultivated land contribute to higher eutrophication then products produced in land occupying facilities such as a factory.

Like the case for the potential acidification, the eutrophication potential is largely due to the solar cell production. The total contribution percentage to the EP impact category from solar cells is 61,5% of the total.

5.3.4 Ozone Depletion potential

Ozone depletion occurs every time an ozone molecule is reduced to oxygen[138]. The gas is on the other hand also formed but the reaction processes. The formation processes will not be described in this LCA due to their extent and complexity. Ozone is both harmful and at the same time vital for earth's biosphere. This is due to the damaging properties of ozone to the biosphere at low altitudes and the beneficial effects of ozone at stratospheric altitudes. Ozone in the stratosphere absorbs 99% of the hazardous incoming UV irradiation, thus protecting life on earth[139]. In order to determine if ozone is good or bad for the biosphere, one has to define what altitude is considered.

Ozone depletion potential regards stratospheric depletion and not ground level ozone. If the ozone layer around the earth is reduced, higher amount of damaging UV radiation will penetrate and affect the biosphere negatively. In the impact category of ODP, reduction of ozone is negative for the environment since the category represents stratospheric ozone only. There are many substances that reduce ozone but all are related to the representative substance for this category which is kg CFC-11-equivalents (kg trichlorofluoromethane equivalents) and thus adjusted to the ability of CFC-11 to degrade ozone.

The main sources for ozone depletion are chlorinated and brominated substances[140]. These substances tend to have a very long residential time in the atmosphere and thus can deplete the ozone layer long after the emissions have occurred.

This impact category is most affected from solar cell production compared to the remaining impact categories, as seen in figure 30. A staggering 94% of the total potential for ozone depletion originates form solar cell production process and 67% of the total ODP is from the solar cell production sub-process "solar cell production". This is not to be confused with the total solar cell production since there is a sub-process sharing the same name. See Appendix 4, figure 61 and Appendix 5, figure 77 data for clarification.

[137] Baumann, H., et.al., p. 156
[138] Ziegel, *Depletion of the stratospheric ozone layer*, retrieved 15 May 2014, <http://www.ziegel.at/gbc-ziegelhandbuch/eng/umwelt/wirkkatodp.htm>
[139] Baumann, H., et.al., p. 150
[140] ibid.

This could be due to the cleaning, polishing and treating compounds used for that stage. Metadata states that several compounds consisting of phosphorous are used in that stage.

5.4 Human effect

5.4.1 Human toxicity potential, 100 years

Human toxicity potential impact category represents emitted compounds that effect human health. It is a very complex category to characterize due to the amount of substances as well as how they affect human health at a certain distance and concentration[141]. HTP is derived from the fate, exposure and effect of a toxic compound during infinite time[142]. All compounds within that impact category are adjusted and presented in kg 1,4-DB-eq (kg 1,4-dichlorobenzene equivalents).

This impact category is probably the most uncertain and debated one of all categories included in this LCA. The category does not account for all toxic compounds in the world and many compounds encountered in our environment have not undergone a risk assessment in order to be included in the HTP impact category[143].

This impact category differs from the already mentioned in the way that solar cell production is not the predominant source for HTP. The production of roof installation, inverter and electric installation contribute to HTP in higher degree. Since solar cells contribute to the most CED, it could be concluded that energy generation has very little to do with the human toxicity potential. The inverter and roof installation production were the predominant resource consuming processes but in that chart the inverter requires more than the roof installation. It seems odd that this ratio is not the same in the HTP impact category until the realization of the difference in metals use. A closer analysis of the ratio between metal use of the three major categories revel that aluminum, cadmium, magnesium and mercury are highest in the roof installation. The excavation and processing of these metals could lead to spills to the environment, thus causing higher results in HTP. The metals could also contribute to human toxicity directly in the processing stages where employees work in close contact with the metals.

5.4.2 Ionizing radiation

Radiation comes from a source with energy content with potential to transfer that energy to a receiving molecule[144]. Ionizing means that an electron can be knocked out of an atom or molecule thus creating a radical which is highly reactive. Non-ionizing radiation on the other hand contains less energy and only excites the electrons, without the ability to knocking them away[145].

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141 ibid., p. 151
142 Building Research Establishment, *Human toxicity*, 2014, retrieved 15 May 2014, <http://www.bre.co.uk/greenguide/page.jsp?id=2098>
143 Building Research Establishment, *Human toxicity*, 2013, retrieved 15 May 2014, <http://www.bre.co.uk/greenguide/page.jsp?id=2098>
144 Uniformed service university of health and science, *What is ionizing radiation*, 2014, retrieved 15 May 2014, <http://www.usuhs.edu/afrri/outreach/ionizing.htm>
145 Division of chemical education, department of chemistry, PURDUE university, *Ionizing radiation*, retrieved 15 May 2014, <http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch23/radiation.php>

Ionizing radiation consists of x-rays, alpha, beta and gamma particles and is continuously all around us, originating from sources such as the ground, universe, water, air, food etc. Ionizing radiation in high does cause damage to the cells and the DNA, which in turn cause higher risk of cell death[146], cell mutation and different diseases.

The impact category of ionizing radiation is presented in DALY (disability adjusted life years). DALY is defined as the sum of years life lost (YLL) and years lived disabled (YLD) from the effect of ionizing radiation.

The ionizing radiation impact category is very similar to the HTP category with one major difference namely the lower impact from electric installation. Ionizing radiation is with high certainty not related to the energy use since solar cells would dominate this category too. It is on the other hand more probable that the resource consumption category is more related to the ionizing radiation. As mentioned, ionizing radiation is emitted from the ground (among others) and by requiring raw materials from mines and excavation sites, more of the ionizing bedrock is brought forth to the surface where the ionizing waves could easier affect the biosphere.

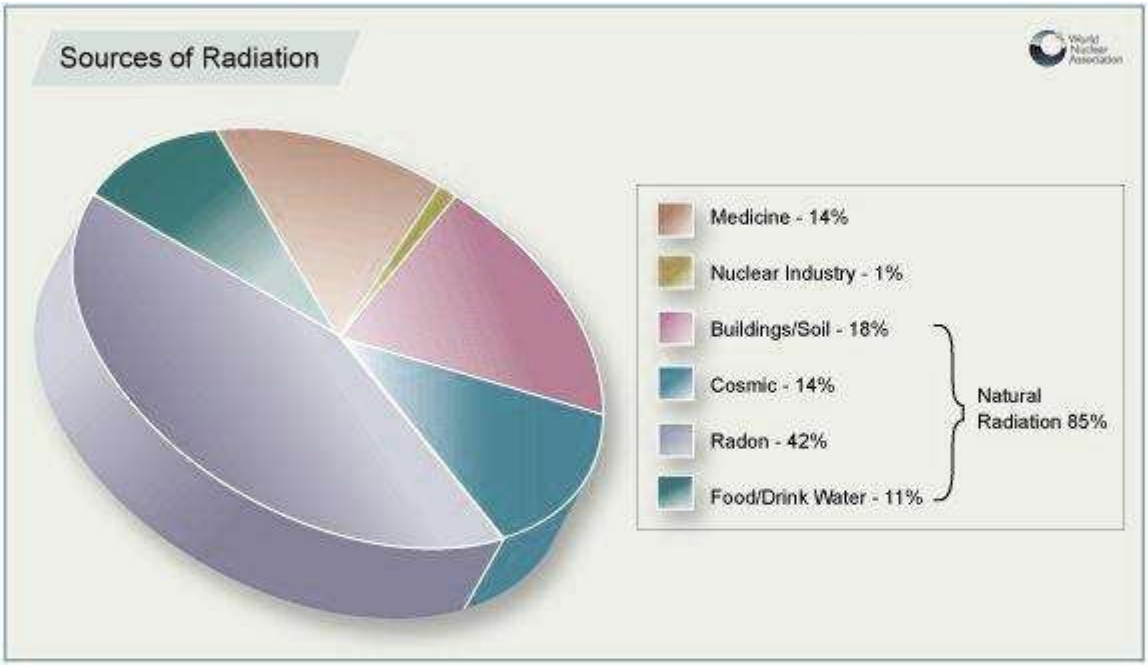

Figure 36: Global radiation sources and quantities affecting the average human population. Source: http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Nuclear-Radiation-and-Health-Effects/

The majority of the radiation affecting humans is derived from building/soil and radon found in soil and bedrock[147] as seen in the figure above.

The majority of ionizing radiation related to the production of the studied PV system is related to raw material excavation from soil and bedrock, consequently resulting increase in exposure of radon (predominantly) to the biosphere.

[146] ibid.
[147] World nuclear association, *Nuclear radiation and health effects*, 2014, retrieved 18 May 2014, http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Nuclear-Radiation-and-Health-Effects/

5.4.3 Energy pay-back time consistency

The energy payback time was calculated in previous section and resulted in a final EPBT of 2,5-3 years. Other reports and projects present similar EPBT as this study. For instance Ecoinvent report no. 6, part XII resulted in 3,2 years for 3 kWp monocrystalline PV system on a slanted roof in Switzerland. According to Eric Alsema, author of many PV studies, the EPBT is between 2,5-3,1 years, with higher irradiation (1700 kWh/m2*year) corresponding to southern Europe, but lower PR (0,75) than this study[148]. Alsema also presented EPBT results for conditions in Netherlands which resulted in 3,5 years[149]. A study by HESPUL showed that the EPBT of monocrystalline PV system, for conditions in Edinburgh, was 3,3 years[150].

[148] Fthenakis, V. et. al., IEA – PVPS – Task 12, *Life cycle inventories and life cycle assessment for photovoltaic systems*, p. 5
[149] ibid.
[150] Gaiddon, B. et.al., *Environmental benefits of PV system in OECD countries*, 2006, HESPUL, p. 4

6 Conclusions

It is clear at this stage that the major cause for the impacts, from the production of the studied PV system, is due to solar cell production. There is great room for further developments of more effective solar cell production processes. The comparison between how the change in thickness of the solar cells also indicates how big impact a small change can have. The results for the thinner solar cells are more representative for this study while the thicker solar cells from Ecoinvent are the base for solar cell production process in detail, step by step. Since the change in thickness is quantitative, it enables a concrete comparison between the cases, and the results are thus representative. The only assumption is that the production processes are identical. Most certainly the production process for thinner solar cells are also more efficient in reality, but are not assumed to be so in this study, due to lack of such data. To which degree the new processes are more efficient is unknown. This study represents industrial processes predominantly from 2005-2006, leading to a time gap in development of almost 10 yeast up to today. It is also inaccurate to make a comparison between production processes using only data of increased efficiency, as the case with the solar cell thickness, since any such data would have to be compared to the Ecoinvent data.

Since the thinner solar cells are more representative in this study, the EPBT should also be so. A energy payback time of 2,5 years for Danish conditions is very good and in line with compared results from other PV studies.

Gaia Solar estimates a lifetime of 30 and 40 years for their PV panels. This difference leads to a 23% reduction of all results. It should be a striving goal to make any possible improvements in order to ensure that the panel endures 40 years lifetime, based on the results from an environmental perspective. It would also be of interest from a financial perspective as well.

The recycling process is not included completely because of the boundaries of the defined system. The biggest, by mass, parts are assumed to be recycled but in reality even more part are recycled such as cables, inverters etc. The solar cells can be used in other products after the expiration of the PV system or could be recycled into a more advanced step of the solar cell production chain. Such an action would improve the environmental results drastically.

This study has assumed the highest impact category values, based on the emission lifetime in the environment, in order to represent a worst case scenario. It has also not assumed the recycling of all parts which in turn also leads to a worst case scenario since the more recycled PV system parts, the better final results. In reality, major contributors to the impact results such as the electric installation and the inverter, would also be recycled, thus leading to even lower results as presented in this study. The lack of data in combination with the time restriction of this study resulted in the exclusion of aspects relating to the extended recycling process.

From an environmental point of view, the company should do adopt every new improvements of the solar cells, be it further thickness reduction or improved production process, since small changes lead to big impacts in the final results when it comes to solar cells. The remaining parts constitute much low part of the total results and should therefore be less prioritized. Any environmental improvement of the remaining parts is of course always a good thing and should also be encouraged, but not to the same degree as the improvement of solar cells should be encouraged.

It is also of great environmental importance to strive to make the solar panels and the whole PV system as long-lasting as possible since it reduces all impact categories and spears more CO_2 emissions.

All presented results, suggestions and conclusions based on the environmental assessment of the PV system should also be weighed against other parameters such as social, economic etc. in order to obtain a complete picture and plan a strategic development of the PV system. The life cycle assessment is not alone meant to be the foundations for decisions, since such actions could be financially catastrophic. This study only enlightens the importance of the environment as one of these parameters which should not be ignored in the strive for a more sustainable and cost efficient future for PV technology.

This study is also in need for newer improved inventory data, representing the new production processes for the PV system parts, especially the solar cell production.

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Appendix 1, Calculations

Recalculation of aluminum recycling from roof installation

950 kg CO_2 is reduced by recycling aluminum from frames.

A approximated value for the aluminum weight of a standard module frame is made in IEA PVPS Task 12, Life cycle inventories and life cycle assessment of photovoltaic systems, page 31. The estimated weight for a 1,6 m^2 module is 4,2 kg resulting in 2,63 kg aluminum/m2 panel.

The weight of a panel in the LCA recycling study is 22,4 kg[151]. The function unit for the study is 1000 kg PV modules. This means that (4,2/22,4)*1000 = 187,5 kg aluminum frame is represented in the LCA recycling study.

In figure 13 the results for aluminum primary materials show that approximately 950 kg CO_2-eq are saved per (FU) 1000 kg modules or 950 kg CO_2-eq are saved per 187,5 kg aluminum. This means that 950/187,5 = 5,07 kg CO_2-eq/kg aluminum is saved.

In the case of this LCA, the roof installation is assumed to consist mostly of aluminum but calculations will be performed in order to represent the aluminum part only. Thus no recycling will be assumed for the other mounting parts.

Roof installation is 3,54 kg/m^2 and of that, 2,2 kg is aluminum. This is the actual data for roof installation provided by Gaia Solar. The roof installation area is 21,37 m^2 thus resulting in a total aluminum mass of 21,37*2,2 = 47 kg. The weight percentage of aluminum from the roof installation is 2,2/3,54=62,2%. This means that only 62,2 % of Ecoinvent data will be allocated and recalculated to represent a case for aluminum recycling.

Presented below is the data for 1 m^2 of roof installation. This data has to be multiplied by 21,37 to represent the case for a 3 000 Wp PV system.

Table 29: Environmental impacts for 1 m^2 roof installation from Ecoinvent.

	Roof installation
Acidification Potential	0,17261
GWP 100a	38,236
Eutrophication Potential	0,084
ODP 10a	2,5739E-06

Data below represent the whole roof installation for a 3 000 Wp system.

[151] Executive summery, Life cycle assessment (LCA) screening of the Maltha recycling process for si-pv modules, http://www.pvcycle.org//wp-content/uploads/Exec-Summary-LCA-Screening-of-a-Recycling-process-of-silicon-based-PV-modules-2012-07.pdf

Table 30: Environmental impacts for 3 000 Wp PV system roof installation, based on Ecoinvent data.

	Roof installation
Acidification Potential	3,68833048
GWP 100a	817,026848
Eutrophication Potential	1,794912
ODP 10a	5,49991E-05

Now the percentage of aluminum, 62,2%, of the total roof installation is extracted and the case for aluminum only is presented below. Basically all the data above is multiplied by 0,62.

Table 31: Environmental impacts for aluminum only, for 3 000 Wp PV system roof installation.

	Roof installation
Acidification Potential	2,212998288
GWP 100a	490,2161088
Eutrophication Potential	1,0769472
ODP 10a	3,29995E-05

This is the data for the aluminum part of the total roof installation. The difference is presented below. It is of importance in order to obtain the remaining materials of the roof installation. The table below thus presents only the remaining weight of the roof installation.

Table 32: Difference in environmental impacts between the whole roof installation and the aluminum parts in a 3 000 kWp PV system.

DIFF

	Roof installation
Acidification Potential	1,475332192
GWP 100a	326,8107392
Eutrophication Potential	0,7179648
ODP 10a	2,19996E-05

The table below shows the saved impact and the final impact from the roof installation aluminum for a 3 000 Wp PV system.

Table 33: Saved and final environmental impacts for the aluminum part of a whole roof installation for a 3 000 Wp PV system.

		Saved	Final
	%	roof installation	roof installation
Acidification Potential	70%	1,549098802	0,663899486
GWP 100a	59%	289,2275042	200,9886046
Eutrophication Potential	40%	0,43077888	0,64616832
ODP 10a	40%	1,31998E-05	1,97997E-05

The ozone depletion potential (ODP) was not presented in the study but will be assumed to equal the lowest presented result. This can be discussed further, but in order to be as honest and trustworthy one cannot assume optimal values for a unknown category. Assuming the lowest value on the other hand is more moral. Therefore the ODP is assumed to be reduced by 40% only.

Below are the final values for recycled aluminum are rejoined with the remaining parts which were not assumed to be recycled, noted as DIFF above.

Table 34: Final recycled aluminum with remaining non-recycled parts of the roof installation and the total final combined results for a 3 000 Wp PV system roof installation with recycled aluminum parts.

	Final	rest mtrl	Sum total roof installation with Al recycling
	roof installation	Roof installation	roof installation
Acidification Potential	0,663899486	1,475332192	2,139231678
GWP 100a	200,9886046	326,8107392	527,7993438
Eutrophication Potential	0,64616832	0,7179648	1,36413312
ODP 10a	1,97997E-05	2,19996E-05	4,17993E-05

Human effect category, land use, water use and resources can unfortunately not be presented because of lack of such impact category data in recycling LCA. Instead they will not be converted and benefited by recycling. The original data, without recycling, will be used for these impact categories.

Recalculation of energy wen recycling aluminum in roof installation

The same method is used to calculate the final energy from the roof installation after including gains in energy from recycling of aluminum in roof installation. Because the recycling LCA only presents energy as a whole category and not as detailed as in this study, per source of energy, all the energy sources will be reduced in equal amount. It is as if all separately presented energy sources in this LCA are added up like the recycling LCA and the recalculated. Each source will thus be lowered by the same percentage. The percentage of energy gain by recycling is obtained from LCA recycling diagram along with the remaining impact categories (global warming potential, acidification potential etc.).

The table below presents the energy required for production of a roof installation from Ecoinvent data before the recycling is considered. Data is adjusted to represent the Gaia Solar case, thus lower than the original roof installation CED.

Table 35: Energy required for the production of a whole roof installation to a 3 000 Wp PV system, with data from Ecoinvent.

	Roof installation
renewable energy resources, biomass	35,3748209
non-renewable energy resources, fossil	2524,593755
non-renewable energy resources, nuclear	645,7200231
non-renewable energy resources, primary forest	0,012912026
renewable energy resources, solar, converted	0,057912996
renewable energy resources, potential (in barrage water), converted	536,3173991
renewable energy resources, kinetic (in wind), converted	4,069656529

The table below is obtained the same way as the aluminum recycling was obtained above. The recalculation steps will thus not be presented here and only the final result will. The final energy use for production of roof installation with recycled aluminum is presented below under the section "final".

Table 36: Percentage reduction, saved and final data for the energy demand when the aluminum is recycled.

(kWh)	Original roof Installation, total	Original aluminum only	Original remaining	saved aluminum %	saved aluminum	final aluminum	final total roof installation, final aluminum + Original remaining
renewable energy resources, biomass	35,37	22,00	13,37	62	13,64	8,36	21,73
non-renewable energy resources, fossil	2524,59	1570,29	954,29	62	973,58	596,71	1551,00
non-renewable energy resources, nuclear	645,72	401,63	244,08	62	249,01	152,62	396,70
non-renewable energy resources, primary forest	0,012	0,0080	0,0048	62	0,0049	0,0030	0,0079
renewable energy resources, solar, converted	0,057	0,036	0,021	62	0,022	0,013	0,035
renewable energy resources, potential (in barrage water), converted	536,31	333,58	202,72	62	206,82	126,76	329,49
renewable energy resources, kinetic (in wind), converted	4,06	2,53	1,53	62	1,56	0,96	2,50

Recalculation of front and back glass with recycling

The recalculation for glass recycling is much easier to conduct since it is presented in only glass data in Ecoinvent contrary to the aluminum in roof installation.

The previous calculations regarding aluminum showed that 187,5 kg of the total 1 000 kg modules was aluminum. The rest is assumed to be glass even dough it is not 100% accurate. A small amount of the PV panel weight is from solar cells, encapsulate and protective back sheet. As presented in this LCA, the mass of these units is almost neglectable in comparison to the weight of the glass.

The glass mass of a standard PV module as presented in IEA PVPS Task 12 report and Ecoinvent report no. XII show that it is 16,1 kg per 1,6 m^2 panel. As mentioned earlier 44,64 panels are required to fulfill the function unit of 1 000 kg of PV modules. 16,1*44,64 = 718 kg glass in the function unit and thus in the results presented.

Figure 13 shows that lowering of global warming impact is 1200 kg CO_2-eq when recycling 718 kg of glass and thus 1200/718 = 1,67 kg CO_2-eq / kg glass. The diagram containing the impact category result show the amount of percentage gains for the categories by recycling. The table below presents the final values for the glass.

Table 37: Original, percentage reduction, saved and final data for the environmental impacts for glass recycling for a 3 000 Wp PV system.

	Original	reduction in %	Saved	Final
GWP, kg CO2-Eq	377,0151	40	150,80604	226,2091
AP, kg SO2-Eq	3,2674565	25	0,816864125	2,450592
EP, kg Nox-Eq	2,124507	55	1,16847885	0,956028
ODP. Kg CFC-11-Eq	4,60383E-05	40	1,84153E-05	2,76E-05

The recycling process spears the production and excavation of new resources in order to obtain glass.

Due to lack of impact categories for human effect, water and land use in the recycling LCA, the gains from recycling will not be implemented on those categories.

Appendix 2, Energy comparison between EG and SoG-silicon pathway and inverter data

Table 38: Electricity required for production of 1 kg purified silicon from two different pathways.

silicon, electronic grade, at plant	silicon, solar grade, modified Siemens process, at plant	MG-silicon, to purification	Mutual (electronic grade silicone + MG silicone purification	Unit	
124,11	45,00	86,64	210,75	kWh	electricity, at cogen 1MWe lean burn. allocation exergy
39,19	65,00	27,36	66,55	kWh	electricity. hydropower, at run-of-river power plant

Table 39: Unit process raw data for MG-silicon from silica sand. Source Ecoinvent.

Explanations	401	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	MG-silicon, at plant	uncertaintyType	StandardDeviation95%
	662			Location						NO		
	493			InfrastructureProcess						0		
	403			Unit						kg		
Technosphere		5		electricity, medium voltage, at grid	NO			0	kWh	11	1	1,101
		5		wood chips, mixed, u=120%, at forest	RER			0	m3	0,003253	1	1,101
		5		hard coal coke, at plant	RER			0	MJ	23,12	1	1,101
		5		graphite, at plant	RER			0	kg	0,1	1	1,101
		5		charcoal, at plant	GLO			0	kg	0,17	1	1,101
		5		petroleum coke, at refinery	RER			0	kg	0,5	1	1,101
		5		silica sand, at plant	DE			0	kg	2,7	1	1,101
		5		oxygen, liquid, at plant	RER			0	kg	0,02	1	1,288
		5		disposal, slag from MG silicon production, 0% water, to inert material landfill	CH			0	kg	0,025	1	1,101
		5		silicone plant	RER			1	unit	1E-11	1	3,052
		5		transport, transoceanic freight ship	OCE			0	tkm	2,55	1	2,096
		5		transport, lorry >16t, fleet average	RER			0	tkm	0,15599	1	2,096
		5		transport, freight, rail	RER			0	tkm	0,069	1	2,096
air, low population density			4	Heat, waste		air	low population density		MJ	71,267	1	1,101
			4	Arsenic		air	low population density		kg	9,4223E-09	1	5,096
			4	Aluminium		air	low population density		kg	1,5508E-06	1	5,096
			4	Antimony		air	low population density		kg	7,8519E-09	1	5,096
			4	Boron		air	low population density		kg	2,7914E-07	1	5,096
			4	Cadmium		air	low population density		kg	3,1408E-10	1	5,096
			4	Calcium		air	low population density		kg	7,7538E-07	1	5,096
			4	Carbon monoxide, biogenic		air	low population density		kg	0,00062027	1	5,096
			4	Carbon monoxide, fossil		air	low population density		kg	0,0013797	1	5,096
			4	Carbon dioxide, biogenic		air	low population density		kg	1,6098	1	1,101
			4	Carbon dioxide, fossil		air	low population density		kg	3,5808	1	1,101
			4	Chromium		air	low population density		kg	7,8519E-09	1	5,096
			4	Chlorine		air	low population density		kg	7,8519E-08	1	1,609
			4	Cyanide		air	low population density		kg	6,8704E-06	1	1,609
			4	Fluorine		air	low population density		kg	3,8769E-08	1	1,609
			4	Hydrogen sulfide		air	low population density		kg	0,0005	1	1,609
			4	Hydrogen fluoride		air	low population density		kg	0,0005	1	1,609
			4	Iron		air	low population density		kg	3,8769E-06	1	5,096
			4	Lead		air	low population density		kg	3,4352E-07	1	5,096
			4	Mercury		air	low population density		kg	7,8519E-09	1	5,096
			4	NMVOC, non-methane volatile organic compounds, unspecified origin		air	low population density		kg	0,000096	1	1,609
			4	Nitrogen oxides		air	low population density		kg	0,0097432	1	1,525
			4	Particulates, > 10 um		air	low population density		kg	0,0077538	1	1,525
			4	Potassium		air	low population density		kg	0,00006203	1	5,096
			4	Silicon		air	low population density		kg	0,0075134	1	5,096
			4	Sodium		air	low population density		kg	7,7538E-07	1	5,096
			4	Sulfur dioxide		air	low population density		kg	0,012241	1	1,135
			4	Tin		air	low population density		kg	7,8519E-09	1	5,096
Outputs			0	MG-silicon, at plant	NO			0	kg	1		

Table 40: Material composition for 1 inverter, 2 400 W. Source Jungbluth, N., et.al., op.cit., p. 105

Component	Unit	Inverter, 2500W, at plant	
		Value	Remarks
Aluminium	kg	1.4	casing
Polycarbonate	kg	-	casing
ABS	kg	-	casing
Poly Ethylene	kg	-	
PVC	kg	0.01	in cable
SAN (Styrene acrylonitrile)	kg	0.01	in cable
copper	kg	0.01	in cable
Steel	kg	9.8	screws and clamps
Printed Circuit Board	cm^2	2246	without components
connector	kg	0.237	
transformers, wire-wound	kg	5.500	
coils	kg	0.351	
IC's	kg	0.028	
transistor	kg	0.038	
transistor diode	kg	0.047	
capacitor, film	kg	0.341	
capacitor, electrolytic	kg	0.256	
capacitor, CMC	kg	0.023	
resistors	kg	0.005	
polyamide injection moulded	kg		
polyester	kg		
Polyethylene, HD	kg		
Paint	kg		
Transformer oil	kg		
Total	kg	18.5	

Appendix 3, Unit process raw data

Table 41: Unit process raw data for solar cells part 1.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	photovoltaic cell, single-Si, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						**18,135 m2**
Technosphere	5		electricity, medium voltage, production UCTE, at grid	UCTE			0	kWh	548,456805
	5		natural gas, burned in industrial furnace low-NOx >100kW	RER			0	MJ	86,442291
	5		light fuel oil, burned in industrial furnace 1MW, non-modulating	RER			0	MJ	21,1109535
	5		photovoltaic cell factory	DE			1	unit	7,254E-06
	5		single-Si wafer, photovoltaics, at plant	RER			0	m2	19,2231
	5		metallization paste, front side, at plant	RER			0	kg	0,13413371
	5		metallization paste, back side, at plant	RER			0	kg	0,08942369
	5		metallization paste, back side, aluminium, at plant	RER			0	kg	1,30408785
	5		ammonia, liquid, at regional storehouse	RER			0	kg	0,12221177
	5		phosphoric acid, fertiliser grade, 70% in H2O, at plant	GLO			0	kg	0,13917524
	5		phosphoryl chloride, at plant	RER			0	kg	0,02892533
	5		titanium dioxide, production mix, at plant	RER			0	kg	2,571E-05
	5		ethanol from ethylene, at plant	RER			0	kg	0,01162508
	5		isopropanol, at plant	RER			0	kg	1,43076083
	5		solvents, organic, unspecified, at plant	GLO			0	kg	0,0260074
	5		silicone product, at plant	RER			0	kg	0,02198325
	5		sodium silicate, spray powder 80%, at plant	RER			0	kg	1,35624411
	5		calcium chloride, CaCl2, at regional storage	CH			0	kg	0,39122636
	5		acetic acid, 98% in H2O, at plant	RER			0	kg	0,05126946
	5		hydrochloric acid, 30% in H2O, at plant	RER			0	kg	0,82715549
	5		hydrogen fluoride, at plant	GLO			0	kg	0,68408847
	5		nitric acid, 50% in H2O, at plant	RER			0	kg	0,48362418
	5		sodium hydroxide, 50% in H2O, production mix, at plant	RER			0	kg	2,84665095
	5		argon, liquid, at plant	RER			0	kg	0,46574307
	5		oxygen, liquid, at plant	RER			0	kg	1,84813785
	5		nitrogen, liquid, at plant	RER			0	kg	33,607782
	5		tetrafluoroethylene, at plant	RER			0	kg	0,05723043
	5		polystyrene, expandable, at plant	RER			0	kg	0,00738493
	5		transport, transoceanic freight ship	OCE			0	tkm	0,5552937

Table 42: Unit process raw data for solar cells part 2.

	5		transport, lorry >16t, fleet average	RER			0	tkm	4,9824099
	5		transport, freight, rail	RER			0	tkm	27,561573
	5		water, completely softened, at plant	RER			0	kg	2489,02875
	5		treatment, PV cell production effluent, to wastewater treatment, class 3	CH			0	m3	3,9414609
	5		disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH			0	kg	5,0001822
resource, in water	4		Water, cooling, unspecified natural origin		resource	in water		m3	18,1081602
air, high population density		4	Heat, waste		air	high population density		MJ	1974,5388
		4	Aluminium		air	high population density		kg	0,01400965
		4	Ethane, hexafluoro-, HFC-116		air	high population density		kg	0,00215099
		4	Hydrogen chloride		air	high population density		kg	0,00482881
		4	Hydrogen fluoride		air	high population density		kg	8,7933E-05
		4	Lead		air	high population density		kg	0,01400965
		4	NMVOC, non-methane volatile organic compounds, unspecified origin		air	high population density		kg	3,5098479
		4	Nitrogen oxides		air	high population density		kg	0,00090675
		4	Methane, tetrafluoro-, R-14		air	high population density		kg	0,00449077
		4	Particulates, < 2.5 um		air	high population density		kg	0,04828806
		4	Silicon		air	high population density		kg	0,00131899
		4	Silver		air	high population density		kg	0,01400965
		4	Sodium		air	high population density		kg	0,00087933
		4	Tin		air	high population density		kg	0,01400965
Outputs		0	photovoltaic cell, single-Si, at plant	RER			0	m2	18,135

Table 43: Unit process raw data for solar cells part 3.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	metallization paste, back side, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						0,0849 kg
Technosphere	5		silver, at regional storage	RER			0	kg	0,05745183
	5		lead, at regional storage	RER			0	kg	0,00685992
	5		chemicals organic, at plant	GLO			0	kg	0,02143725
	5		electricity, medium voltage, production UCTE, at grid	UCTE			0	kWh	0,021225
	5		natural gas, burned in industrial furnace low-NOx >100kW	RER			0	MJ	0,0702972
	5		transport, lorry >16t, fleet average	RER			0	tkm	0,0085749
	5		transport, freight, rail	RER			0	tkm	0,0514494
	5		solder production plant	RER			1	unit	1,698E-11
air, high population density		4	Heat, waste		air	high population density		MJ	0,07641
Outputs		0	metallization paste, back side, at plant	RER			0	kg	0,0849

Table 44: Unit process raw data for solar cells part 4.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	metallization paste, back side, aluminium, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						1,304 kg
Technosphere	5		aluminium, primary, at plant	RER			0	kg	1,053632
	5		silica sand, at plant	DE			0	kg	0,0395112
	5		chemicals organic, at plant	GLO			0	kg	0,2238968
	5		electricity, medium voltage, production UCTE, at grid	UCTE			0	kWh	0,326
	5		natural gas, burned in industrial furnace low-NOx >100kW	RER			0	MJ	1,079712
	5		transport, lorry >16t, fleet average	RER			0	tkm	0,131704
	5		transport, freight, rail	RER			0	tkm	0,790224
	5		solder production plant	RER			1	unit	2,608E-10
air, high population density		4	Heat, waste		air	high population density		MJ	1,1736
Outputs		0	metallization paste, back side, aluminium, at plant	RER			0	kg	1,304

Table 45: Unit process raw data for production of the inverters.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	inverter, 2500W, at plant
			Location						RER
			InfrastructureProcess						1
			Unit						**2 unit**
Technosphere	5		electricity, medium voltage, production UCTE, at grid	UCTE			0	kWh	42,4
	5		aluminium, production mix, cast alloy, at plant	RER			0	kg	2,8
	5		copper, at regional storage	RER			0	kg	11,02
	5		steel, low-alloyed, at plant	RER			0	kg	19,6
	5		styrene-acrylonitrile copolymer, SAN, at plant	RER			0	kg	0,02
	5		polyvinylchloride, at regional storage	RER			0	kg	0,02
	5		printed wiring board, through-hole, at plant	GLO			0	m2	0,4492
	5		connector, clamp connection, at plant	GLO			0	kg	0,474
	5		inductor, ring core choke type, at plant	GLO			0	kg	0,702
	5		integrated circuit, IC, logic type, at plant	GLO			0	kg	0,056
	5		transistor, wired, small size, through-hole mounting, at plant	GLO			0	kg	0,076
	5		diode, glass-, through-hole mounting, at plant	GLO			0	kg	0,094
	5		capacitor, film, through-hole mounting, at plant	GLO			0	kg	0,682
	5		capacitor, electrolyte type, > 2cm height, at plant	GLO			0	kg	0,512
	5		capacitor, Tantalum-, through-hole mounting, at plant	GLO			0	kg	0,046
	5		resistor, metal film type, through-hole mounting, at plant	GLO			0	kg	0,01
	5		sheet rolling, steel	RER			0	kg	19,6
	5		wire drawing, copper	RER			0	kg	11,02
	5		section bar extrusion, aluminium	RER			0	kg	2,8
	5		metal working factory	RER			1	unit	1,79444E-08
	5		corrugated board, mixed fibre, single wall, at plant	RER			0	kg	5
	5		polystyrene foam slab, at plant	RER			0	kg	0,6
	5		fleece, polyethylene, at plant	RER			0	kg	0,12
	5		transport, lorry >16t, fleet average	RER			0	tkm	4,5992
	5		transport, freight, rail	RER			0	tkm	14,2268
	5		transport, transoceanic freight ship	OCE			0	tkm	72,542
	5		disposal, packaging cardboard, 19.6% water, to municipal incineration	CH			0	kg	5
	5		disposal, polystyrene, 0.2% water, to municipal incineration	CH			0	kg	0,62
	5		disposal, polyethylene, 0.4% water, to municipal incineration	CH			0	kg	0,12
	5		disposal, treatment of printed wiring boards	GLO			0	kg	3,4056
air, high population density		4	Heat, waste		air	high population density		MJ	152,64
Outputs		0	inverter, 2500W, at plant	RER			1	unit	2

Table 46: Unit process raw data for the electric installation.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	electric installation, photovoltaic plant, at plant
			Location						CH
			InfrastructureProcess						1
			Unit						unit
Technosphere	5		copper, at regional storage	RER			0	kg	14,7
	5		brass, at plant	CH			0	kg	0,02
	5		zinc, primary, at regional storage	RER			0	kg	0,04
	5		steel, low-alloyed, at plant	RER			0	kg	0,86
	5		nylon 6, at plant	RER			0	kg	0,23
	5		polyethylene, HDPE, granulate, at plant	RER			0	kg	17,61
	5		polyvinylchloride, bulk polymerised, at plant	RER			0	kg	2,13
	5		polycarbonate, at plant	RER			0	kg	0,2
	5		epoxy resin, liquid, at plant	RER			0	kg	0,002
	5		wire drawing, copper	RER			0	kg	14,7
	5		transport, lorry 20-28t, fleet average	CH			0	tkm	2,1475
	5		transport, freight, rail	CH			0	tkm	13,406
	5		disposal, plastic, industr. electronics, 15.3% water, to municipal incineration	CH			0	kg	20,172
	5		disposal, building, electric wiring, to final disposal	CH			0	kg	0,06
Outputs		0	electric installation, photovoltaic plant, at plant	CH			1	unit	1

Table 47: Unit process raw data for the encapsulate.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	ethylvinylacetate, foil, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						18,282 kg
Technosphere	5		ethylene vinyl acetate copolymer, at plant	RER			0	kg	18,64764
	5		extrusion, plastic film	RER			0	kg	18,64764
	5		transport, lorry >16t, fleet average	RER			0	tkm	1,8282
	5		transport, freight, rail	RER			0	tkm	3,6564
Outputs		0	ethylvinylacetate, foil, at plant	RER			0	kg	18,282

Table 48: Unit process raw data for front and back glass.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	flat glass, uncoated, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						**385 kg**
Technosphere	5		electricity, medium voltage, production UCTE, at grid	UCTE			0	kWh	42,735
	5		transport, lorry >16t, fleet average	RER			0	tkm	23,2155
	5		disposal, municipal solid waste, 22.9% water, to municipal incineration	CH			0	kg	0,4235
	5		flat glass plant	RER			1	unit	9,2785E-08
	5		heavy fuel oil, at regional storage	RER			0	kg	28,413
	5		hydrogen, liquid, at plant	RER			0	kg	0,001386
	5		limestone, milled, packed, at plant	CH			0	kg	154
	5		natural gas, high pressure, at consumer	RER			0	MJ	1755,6
	5		nitrogen, liquid, at plant	RER			0	kg	1,90575
	5		refractory, fireclay, packed, at plant	DE			0	kg	0,41195
	5		silica sand, at plant	DE			0	kg	222,53
	5		soda, powder, at plant	RER			0	kg	88,165
	5		steel, converter, unalloyed, at plant	RER			0	kg	0,0052745
	5		tin, at regional storage	RER			0	kg	0,0035266
	5		treatment, sewage, from residence, to wastewater treatment, class 2	CH			0	m3	0,13475
resource, in water	4		Water, cooling, unspecified natural origin		resource	in water		m3	0,2695
air, unspecified		4	Carbon dioxide, fossil		air	unspecified		kg	266,805
		4	Carbon monoxide, fossil		air	unspecified		kg	0,01925
		4	Hydrogen chloride		air	unspecified		kg	0,0356125
		4	Hydrogen fluoride		air	unspecified		kg	0,008085
		4	Nitrogen oxides		air	unspecified		kg	1,25895
		4	NMVOC, non-methane volatile organic compounds, unspecified origin		air	unspecified		kg	0,01925
		4	Particulates, < 2.5 um		air	unspecified		kg	0,07084
		4	Particulates, > 10 um		air	unspecified		kg	0,008855
		4	Particulates, > 2.5 um, and < 10um		air	unspecified		kg	0,008855
		4	Sulfur dioxide		air	unspecified		kg	1,5554
		4	Tin		air	unspecified		kg	0,00351505
Outputs		0	flat glass, uncoated, at plant	RER			0	kg	385

Table 49: Unit process raw data for protective back sheet, part 1.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	polyethylene, HDPE, granulate, at plant
			Location						RER
			InfrastructureProcess						0
			Unit						**0,127 kg**
Technosphere	5		disposal, facilities, chemical production	RER			0	kg	8,03237E-11
	5		disposal, municipal solid waste, 22.9% water, to municipal incineration	CH			0	kg	0,000345338
	5		disposal, average incineration residue, 0% water, to residual material landfill	CH			0	kg	0,001279271
	5		disposal, wood untreated, 20% water, to municipal incineration	CH			0	kg	5,59753E-09
	5		disposal, plastics, mixture, 15.3% water, to municipal incineration	CH			0	kg	8,05269E-05
	5		disposal, hazardous waste, 25% water, to hazardous waste incineration	CH			0	kg	0,000632193
resource, in ground	4		Oil, crude, in ground		resource	in ground		kg	0,11522202
	4		Gas, natural, in ground		resource	in ground		Nm3	0,09278366
	4		Coal, hard, unspecified, in ground		resource	in ground		kg	0,01295527
	4		Coal, brown, in ground		resource	in ground		kg	3,60921E-07
resource, biotic	4		Peat, in ground		resource	biotic		kg	0,000243192
resource, in ground	4		Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground		resource	in ground		kg	1,92138E-06
	4		Talc, in ground		resource	in ground		kg	1,11816E-27
	4		Sodium nitrate, in ground		resource	in ground		kg	5,49567E-11
	4		Sodium chloride, in ground		resource	in ground		kg	4,45884E-05
	4		Shale, in ground		resource	in ground		kg	1,18716E-06
	4		Sand, unspecified, in ground		resource	in ground		kg	1,06429E-05
	4		Sulfur, in ground		resource	in ground		kg	6,57885E-06
	4		TiO2, 95% in rutile, 0.40% in crude ore, in ground		resource	in ground		kg	1,3923E-34
	4		Sylvite, 25 % in sylvinite, in ground		resource	in ground		kg	8,00799E-10
	4		Phosphorus, 18% in apatite, 12% in crude ore, in ground		resource	in ground		kg	1,39662E-13
	4		Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground		resource	in ground		kg	6,43992E-08
	4		Olivine, in ground		resource	in ground		kg	2,07645E-07
	4		Nickel, 1.98% in silicates, 1.04% in crude ore, in ground		resource	in ground		kg	3,67119E-11

Table 50: Unit process raw data for protective back sheet, part 2.

	4		Magnesite, 60% in crude ore, in ground	resource	in ground		kg	1,83185E-11
	4		Cinnabar, in ground	resource	in ground		kg	8,99655E-11
	4		Gravel, in ground	resource	in ground		kg	8,16521E-08
	4		Granite, in ground	resource	in ground		kg	5,93573E-16
	4		Fluorspar, 92%, in ground	resource	in ground		kg	4,01409E-08
	4		Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	resource	in ground		kg	2,85572E-08
	4		Feldspar, in ground	resource	in ground		kg	7,80987E-18
	4		Iron, 46% in ore, 25% in crude ore, in ground	resource	in ground		kg	2,21323E-05
	4		Dolomite, in ground	resource	in ground		kg	2,71018E-07
	4		Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	resource	in ground		kg	4,06565E-10
	4		Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	resource	in ground		kg	1,29477E-13
	4		Clay, unspecified, in ground	resource	in ground		kg	3,56146E-11
	4		Calcite, in ground	resource	in ground		kg	1,69101E-05
	4		Anhydrite, in ground	resource	in ground		kg	4,19329E-07
	4		Clay, bentonite, in ground	resource	in ground		kg	4,19837E-06
	4		Aluminium, 24% in bauxite, 11% in crude ore, in ground	resource	in ground		kg	1,53518E-07
	4		Barite, 15% in crude ore, in ground	resource	in ground		kg	6,86689E-09
	4		Uranium, in ground	resource	in ground		kg	1,09201E-06
resource, biotic	4		Wood, unspecified, standing	resource	biotic		m3	4,24307E-10
resource, in water	4		Energy, potential (in hydropower reservoir), converted	resource	in water		MJ	0,07406767
resource, biotic	4		Energy, gross calorific value, in biomass	resource	biotic		MJ	0,03971798
resource, in water	4		Water, unspecified natural origin	resource	in water		m3	0,000277114
	4		Water, river	resource	in water		m3	0,0001232
	4		Water, salt, ocean	resource	in water		m3	1,66434E-05
	4		Water, well, in ground	resource	in water		m3	1,20965E-05
	4		Water, cooling, unspecified natural origin	resource	in water		m3	0,003673348
air, high population density		4	Heat, waste	air	high population density		MJ	2,844038

Table 51: Unit process raw data for protective back sheet, part 3.

		4	Particulates, > 10 um		air	high population density		kg	2,61315E-05
		4	Particulates, > 2.5 um, and < 10um		air	high population density		kg	3,51142E-05
		4	Particulates, < 2.5 um		air	high population density		kg	2,04153E-05
		4	Carbon monoxide, fossil		air	high population density		kg	0,001559179
		4	Carbon monoxide, biogenic		air	high population density		kg	1,08577E-05
		4	Carbon dioxide, fossil		air	high population density		kg	0,197612
		4	Carbon dioxide, biogenic		air	high population density		kg	0,001376045
		4	Sulfur dioxide		air	high population density		kg	0,000517716
		4	Hydrogen sulfide		air	high population density		kg	7,42074E-10
		4	Nitrogen oxides		air	high population density		kg	0,00041021
		4	Ammonia		air	high population density		kg	2,75057E-11
		4	Chlorine		air	high population density		kg	4,62039E-12
		4	Hydrogen chloride		air	high population density		kg	7,8406E-06
		4	Fluorine		air	high population density		kg	2,09614E-12
		4	Hydrogen fluoride		air	high population density		kg	2,30073E-07
		4	NMVOC, non-methane volatile organic compounds, unspecified origin		air	high population density		kg	0,000546354
		4	Aldehydes, unspecified		air	high population density		kg	1,87198E-16
		4	Lead		air	high population density		kg	1,49098E-10
		4	Mercury		air	high population density		kg	3,01841E-10
		4	Sulfate		air	high population density		kg	2,28765E-16
		4	Dinitrogen monoxide		air	high population density		kg	1,00501E-13
		4	Hydrogen		air	high population density		kg	5,25755E-06
		4	Ethane, 1,2-dichloro-		air	high population density		kg	3,22199E-12
		4	Ethene, chloro-		air	high population density		kg	6,37261E-11
		4	Hydrocarbons, chlorinated		air	high population density		kg	1,26643E-10

Table 52: Unit process raw data for protective back sheet, part 4.

		4	Cyanide		air	high population density		kg	6,20573E-20
		4	Methane, fossil		air	high population density		kg	0,0017907
		4	Methane, biogenic		air	high population density		kg	1,247E-05
		4	Hydrocarbons, aromatic		air	high population density		kg	1,08619E-05
		4	Hydrocarbons, aliphatic, alkanes, cyclic		air	high population density		kg	1,35534E-19
		4	Carbon disulfide		air	high population density		kg	1,88443E-12
		4	Methane, dichloro-, HCC-30		air	high population density		kg	3,75984E-15
		4	Copper		air	high population density		kg	2,86398E-13
		4	Arsenic		air	high population density		kg	1,56655E-11
		4	Cadmium		air	high population density		kg	6,68185E-12
		4	Silver		air	high population density		kg	2,90322E-25
		4	Zinc		air	high population density		kg	1,64122E-10
		4	Chromium		air	high population density		kg	7,13207E-11
		4	Selenium		air	high population density		kg	1,00548E-26
		4	Nickel		air	high population density		kg	1,77368E-14
		4	Antimony		air	high population density		kg	2,50977E-12
		4	Ethene		air	high population density		kg	2,0607E-07
		4	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin		air	high population density		kg	4,02488E-33
		4	Benzene		air	high population density		kg	3,34848E-19
		4	Toluene		air	high population density		kg	5,60832E-20
		4	Xylene		air	high population density		kg	2,59245E-20
		4	Benzene, ethyl-		air	high population density		kg	1,9666E-20

Table 53: Unit process raw data for protective back sheet, part 5.

		4	Styrene		air	high population density		kg	2,76377E-21
		4	Propene		air	high population density		kg	1,52641E-07
water, river		4	COD, Chemical Oxygen Demand		water	river		kg	2,41567E-05
		4	BOD5, Biological Oxygen Demand		water	river		kg	2,65506E-06
		4	Lead		water	river		kg	1,48971E-10
		4	Iron, ion		water	river		kg	2,08191E-09
		4	Sodium, ion		water	river		kg	9,78103E-06
		4	Acidity, unspecified		water	river		kg	2,4873E-07
		4	Nitrate		water	river		kg	2,85204E-07
		4	Mercury		water	river		kg	2,78435E-11
		4	Ammonium, ion		water	river		kg	3,94386E-07
		4	Chloride		water	river		kg	1,98831E-05
		4	Cyanide		water	river		kg	2,09906E-12
		4	Fluoride		water	river		kg	1,8067E-10
		4	Sulfide		water	river		kg	7,21665E-14
		4	Hydrocarbons, unspecified		water	river		kg	1,81508E-06
		4	Suspended solids, unspecified		water	river		kg	2,48082E-05
		4	Oils, unspecified		water	river		kg	7,60425E-07
		4	Chlorinated solvents, unspecified		water	river		kg	7,31977E-10
		4	Chlorine		water	river		kg	1,34925E-10
		4	Phenol		water	river		kg	2,37173E-07
		4	Dissolved solids		water	river		kg	2,71628E-06
		4	Phosphorus		water	river		kg	2,24447E-08
		4	Nitrogen		water	river		kg	1,40424E-07
		4	Sulfate		water	river		kg	0,000105221
		4	Ethane, 1,2-dichloro-		water	river		kg	6,42531E-14
		4	Ethene, chloro-		water	river		kg	1,1737E-12
		4	Potassium, ion		water	river		kg	8,59396E-08
		4	Calcium, ion		water	river		kg	3,67144E-07
		4	Magnesium		water	river		kg	1,2234E-10
		4	Chromium, ion		water	river		kg	1,75933E-13
		4	Chlorate		water	river		kg	1,26195E-08
		4	Bromate		water	river		kg	7,0485E-11
		4	TOC, Total Organic Carbon		water	river		kg	1,40792E-06
		4	AOX, Adsorbable Organic Halogen as Cl		water	river		kg	1,33426E-13
		4	Aluminium		water	river		kg	7,07365E-08
		4	Zinc, ion		water	river		kg	1,69012E-08
		4	Copper, ion		water	river		kg	1,97104E-08
		4	Nickel, ion		water	river		kg	4,72961E-11
		4	Carbonate		water	river		kg	3,66954E-06
		4	Arsenic, ion		water	river		kg	2,52006E-11
		4	Cadmium, ion		water	river		kg	1,40754E-12
		4	Manganese		water	river		kg	1,98184E-11
		4	Tin, ion		water	river		kg	9,50849E-12
		4	Strontium		water	river		kg	1,34087E-12
		4	Silicon		water	river		kg	3,86982E-21
		4	Benzene		water	river		kg	7,08762E-23
Outputs		0	polyethylene, HDPE, granulate, at plant	RER			0	kg	0,127

Table 54: Unit process raw data for AR-coating.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	anti-reflex-coating, etching, solar glass
			Location						DK
			InfrastructureProcess						0
			Unit						21,35 m2
Technosphere	5		natural gas, burned in industrial furnace low-NOx >100kW	RER			0	MJ	155,001
	5		electricity, low voltage, at grid	DK			0	kWh	25,62
	5		glass etching plant	DK			1	unit	0,00000427
	5		tap water, at user	RER			0	kg	213,5
	5		fluosilicic acid, 22% in H2O, at plant	RER			0	kg	2,83955
	5		lime, hydrated, packed, at plant	CH			0	kg	0,427
	5		treatment, sewage, unpolluted, from residence, to wastewater treatment, class 2	CH			0	m3	0,2135
	5		disposal, refinery sludge, 89.5% water, to sanitary landfill	CH			0	kg	0,53375
	5		transport, lorry >16t, fleet average	RER			0	tkm	0,326655
	5		transport, freight, rail	RER			0	tkm	0,655445
water, river		4	Fluoride		water	river		kg	0,010675
Outputs		0	anti-reflex-coating, etching, solar glass	DK			0	m2	21,35

Table 55: Unit process raw data for slanted roof installation.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	slanted-roof construction, mounted, on roof
			Location						RER
			InfrastructureProcess						1
			Unit						**21,368 m2**
Technosphere	5		aluminium, production mix, wrought alloy, at plant	RER			0	kg	60,588964
	5		corrugated board, mixed fibre, single wall, at plant	RER			0	kg	2,84878176
	5		polyethylene, HDPE, granulate, at plant	RER			0	kg	0,029985714
	5		polystyrene, high impact, HIPS, at plant	RER			0	kg	0,149932846
	5		steel, low-alloyed, at plant	RER			0	kg	32,0498632
	5		section bar extrusion, aluminium	RER			0	kg	64,7706816
	5		sheet rolling, steel	RER			0	kg	32,0498632
	5		transport, lorry >16t, fleet average	RER			0	tkm	4,81356936
	5		transport, freight, rail	RER			0	tkm	31,9537072
	5		transport, van <3.5t	RER			0	tkm	9,28183184
	5		disposal, packaging cardboard, 19.6% water, to municipal incineration	CH			0	kg	2,84878176
	5		disposal, building, polyethylene/polypropylene products, to final disposal	CH			0	kg	0,029985714
	5		disposal, building, polystyrene isolation, flame-retardant, to final disposal	CH			0	kg	0,149932846
Outputs		0	slanted-roof construction, mounted, on roof	RER			1	m2	21,368

Table 56: Unit process raw data for freight ship transport.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	transport, transoceanic freight ship
			Location						OCE
			InfrastructureProcess						0
			Unit						291,2 tkm
Technosphere	5		operation, transoceanic freight ship	OCE			0	tkm	291,2
	5		transoceanic freight ship	OCE			1	unit	4,48448E-09
	5		maintenance, transoceanic freight ship	RER			1	unit	4,48448E-09
	5		port facilities	RER			1	unit	3,69824E-12
	5		operation, maintenance, port	RER			1	unit	3,69824E-10
Outputs		0	transport, transoceanic freight ship	OCE			0	tkm	291,2

Table 57: Unit process raw data for transport by lorry, 3,5-7,5 tons.

Explanations	Input-Group	Output-Group	Name	Location	Infrastructure-Process	Unit	transport, lorry 3.5-7.5t, EURO5
			Location				RER
			InfrastructureProcess				0
			Unit				**25 tkm**
Technosphere	5		operation, lorry 3.5-7.5t, EURO5	RER	0	vkm	25,515
	5		lorry 16t	RER	1	unit	0,00004725
	5		maintenance, lorry 16t	CH	1	unit	0,00004725
	5		disposal, lorry 16t	CH	1	unit	0,00004725
	5		road	CH	1	ma	0,072165
	5		operation, maintenance, road	CH	1	ma	0,029905
	5		disposal, road	RER	1	ma	0,072165
Outputs		0	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	25

Table 58: Unit process raw data for transport by lorry, 16-32 tons.

Explanations	Input-Group	Output-Group	Name	Location	Category	Sub-Category	Infrastructure-Process	Unit	transport, lorry 16-32t, EURO5
			Location						RER
			InfrastructureProcess						0
			Unit						**473,2 tkm**
Technosphere	5		operation, lorry 16-32t, EURO5	RER			0	vkm	82,081272
	5		lorry 28t	RER			1	unit	0,000152006
	5		maintenance, lorry 28t	CH			1	unit	0,000152006
	5		disposal, lorry 28t	CH			1	unit	0,000152006
	5		road	CH			1	ma	0,6120842
	5		operation, maintenance, road	CH			1	ma	0,096206292
	5		disposal, road	RER			1	ma	0,6120842
Outputs		0	transport, lorry 16-32t, EURO5	RER			0	tkm	473,2

Appendix 4, Metadata

Table 59: Metadata for silica sand.

Type	ID	Field name	
ReferenceFunction	401	Name	silica sand, at plant
Geography	662	Location	DE
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	kg
DataSetInformation	201	Type	2
	202	Version	2,1
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	283
	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
Technology	692	Text	typical technology for Swiss production
	404	Amount	1
	490	LocalName	Quarzsand, ab Werk
	491	Synonyms	
	492	GeneralComment	There is almost no difference from the module "sand, at mine". Some more transportation and energy for drying is added. For the calculation of the additional requirement of conveyor belt the total yearly production of a German company (450'000 tons) and a lifespan of 20 years are used.
Representativeness	722	Percent	
	724	ProductionVolume	unknown
	725	SamplingProcedure	literature and estimations
	726	Extrapolations	See geography
	727	UncertaintyAdjustments	none

Type	ID	Field name	
ReferenceFunction	401	Name	silica sand, at plant
Geography	662	Location	DE
ReferenceFunction	493	InfrastructureProce	0
ReferenceFunction	403	Unit	kg
	494	InfrastructureIncluded	1
	495	Category	construction materials
	496	SubCategory	additives
	497	LocalCategory	Mineralische Baustoffe
	498	LocalSubCategory	Zuschlags-Füllstoffe
	499	Formula	SiO2
	501	StatisticalClassification	
	502	CASNumber	
Geography	663	Text	The amount of energy used for drying sand is a Swiss data.
	602	EndDate	2001
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
	402	IncludedProcesses	includes the raw material "sand, at plant", a certain additional amount of conveyor belt and the energy for drying the sand. No requirements for administration are included.
DataGeneratorAndPublication	751	Person	289
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	138
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
DataSetInformation	208	ImpactAssessmentResult	1
ProofReading	5616	Validator	320
	5615	Details	passed
	5619	OtherDetails	
TimePeriod	601	StartDate	1998

Table 60: Metadata for MG-silicon.

Type	Field name				
ReferenceFunction	Name	MG-silicon, at plant	TimePeriod	StartDate	2000
Geography	Location	NO		EndDate	2002
ReferenceFunction	InfrastructureProcess	0,00		DataValidForEntirePeriod	1,00
ReferenceFunction	Unit	kg		OtherPeriodText	Time of publication.
DataSetInformation	Type	1,00	Geography	Text	Production plants in NO.
	Version	2,10	Technology	Text	Modern technology, waste heat is partly recovered and used for electricity generation and/or district heating.
	energyValues	0,00	Representativeness	Percent	50,00
	LanguageCode	en		ProductionVolume	1'000'000t in 2000. Most of European plants are located in NO.
	LocalLanguageCode	de		SamplingProcedure	Publication of plant specific data in a European survey.
DataEntryBy	Person	297,00		Extrapolations	Air emissions of different pollutants are extrapolated from environmental reports.
	QualityNetwork	1,00		UncertaintyAdjustments	none
ReferenceFunction	DataSetRelatesToProduct	1,00	DataGeneratorAndPublication	Person	297,00
	IncludedProcesses	Gate to gate inventory for production of MG-silicon from silica sand including materials, energy use, wastes and air emissions. Emissions to water are not available.		DataPublishedIn	2,00
	Amount	1,00		ReferenceToPublishedSource	202,00
	LocalName	MG-Silizium, ab Werk		Copyright	1,00
	Synonyms	metal grade silicon		AccessRestrictedTo	0,00
	GeneralComment	MG-silicon with a purity of 99%. Used for the production of aluminium compounds, silicones and semiconductors. For the use in semiconductors further purification is necessary.		CompanyCode	
	InfrastructureIncluded	1,00		CountryCode	
	Category	metals		PageNumbers	basic silicon
	SubCategory	extraction	DataSetInformation	ImpactAssessmentResult	0,00
	LocalCategory	Metalle	ProofReading	Validator	320,00
	LocalSubCategory	Gewinnung		Details	Passed.
	Formula	Si		OtherDetails	none
	StatisticalClassification				
	CASNumber	007440-21-3			

Table 61: Metadata for SoG-silicon.

ReferenceFunction	Name	silicon, solar grade, modified Siemens process, at plant		TimePeriod	StartDate	2004
Geography	Location	RER			EndDate	2005
ReferenceFunction	InfrastructureProcess	0,00			DataValidForEntirePeriod	1,00
ReferenceFunction	Unit	kg			OtherPeriodText	Time of investigation
DataSetInformation	Type	2,00		Geography	Text	Data for different types of processes in Europe and North America.
	IncludedProcesses	Gate to gate inventory for the production of high purity polycrystalline silicon from MG-silicon in actual processes. Only energy use, chemicals and yield are known. Emissions to water are roughly estimated.		Technology	Text	Production with Siemens process either from SiHCl3 or SiH4. Partly with standard Siemens process and partly with modified Siemens ("solar grade") at reduced electricity consumption. Mix of electricity supply in accordance with actual conditions at considered production locations.
	energyValues	0,00		Representativeness	Percent	75,00
	LanguageCode	en			ProductionVolume	12600 t in 2005
	LocalLanguageCode	de			SamplingProcedure	Average of data from one company and estimated data from another company based on literature data
DataEntryBy	Person	297,00			Extrapolations	Emissions to water are estimated with figures investigated for MG-silicon purification to EG-silicon with a similar type of process.
	QualityNetwork	1,00			UncertaintyAdjustments	none
ReferenceFunction	DataSetRelatesToProduct	1,00		DataGeneratorAndPublication	Person	343,00
	Version	2,10			DataPublishedIn	2,00
	Amount	1,00			ReferenceToPublishedSource	202,00
	LocalName	Silizium, Solaranwendung, modifizierter Siemens Prozess, ab Werk			Copyright	1,00
	Synonyms	SoG-Silicon//polycrystaline			AccessRestrictedTo	0,00
	GeneralComment	Process for silicon used in photovoltaic industry. Purity >98% sufficient for use in photovoltaic industry.			CompanyCode	
	InfrastructureIncluded	1,00			CountryCode	
	Category	metals			PageNumbers	crystalline silicon
	SubCategory	refinement		DataSetInformation	ImpactAssessmentResult	1,00
	LocalCategory	Metalle		ProofReading	Validator	320,00
	LocalSubCategory	Veredelung			Details	Passed.
	Formula	Si			OtherDetails	none
	StatisticalClassification					
	CASNumber	007440-21-3				

Table 62: Metadata for silicon production mix.

ReferenceFunction	Name	silicon, production mix, photovoltaics, at plant		OtherPeriodText	Time of investigation
Geography	Location	GLO		InfrastructureIncluded	1,00
ReferenceFunction	InfrastructureProcess	0,00		Category	metals
ReferenceFunction	Unit	kg		SubCategory	refinement
DataSetInformation	Type	2,00		LocalCategory	Metalle
	Version	2,10		LocalSubCategory	Veredelung
	energyValues	0,00		Formula	Si
	LanguageCode	en		StatisticalClassification	
	LocalLanguageCode	de		CASNumber	007440-21-3
DataEntryBy	Person	297,00	TimePeriod	StartDate	2005
	QualityNetwork	1,00		EndDate	2005
ReferenceFunction	DataSetRelatesToProduct	1,00		DataValidForEntirePeriod	1,00
	IncludedProcesses	Production mix for the purified silicon feedstock used for sc- and mc-Si cell in photovoltaics. The global production mix is represented partly as it was not possible to include all existing production routes and all production locations in the assessment.		GeneralComment	Production mix of different feedstock for silicon used in photovoltaic industry. Purity >98% sufficient for use in photovoltaic industry
	Amount	1,00	Geography	Text	Data for the worldwide consumption.
	LocalName	Silizium, Produktionsmix, Photovoltaik, ab Werk	DataGeneratorAndPublicatio	Person	297,00
	Synonyms	0,00		DataPublishedIn	2,00
Technology	Text	Market mix of different technologies.		ReferenceToPublishedSource	202,00
Representativeness	Percent	90,00		Copyright	1,00
	ProductionVolume	15000 t in 2005		AccessRestrictedTo	0,00
	SamplingProcedure	Literature.		CompanyCode	
	Extrapolations	none		CountryCode	
	UncertaintyAdjustments	none		PageNumbers	crystalline silicon
			DataSetInformation	ImpactAssessmentResult	1,00
			ProofReading	Validator	320,00
				Details	Passed.
				OtherDetails	none

Table 63: Metadata for CZ single silicon.

ReferenceFunction	Name	CZ single crystalline silicon, photovoltaics, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	kg
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	297,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Gate to gate inventory for an improved Czochralski process. Crushing of Si, etching with HNO3, HF and acetic acid. Melting in a silica pot and crystallisation to produce a monocrystalline material. Water emissions roughly estimated. Process emissions to air are not known.
	Amount	1,00
	LocalName	CZ single-Silizium, Photovoltaik, ab Werk
	Synonyms	Czochralski process
	GeneralComment	Production of a monocrystalline block with a diameter of 130mm and a length of 150cm. Losses of non-recycled material due to block cutting are included.
Representativeness	Percent	10,00
	ProductionVolume	not known
	SamplingProcedure	Publication of plant specific (partly aggregated) data and literature information.
	Extrapolations	none
	UncertaintyAdjustments	none

	InfrastructureIncluded	1,00
	Category	photovoltaic
	SubCategory	production of components
	LocalCategory	Photovoltaik
	LocalSubCategory	Herstellung Komponenten
	Formula	Si
	StatisticalClassification	
	CASNumber	007440-21-3
TimePeriod	StartDate	1992
	EndDate	2006
	DataValidForEntirePeriod	1,00
	OtherPeriodText	Most data are published in 2006. Some older data published in 1992.
Technology	Text	Czochralski process for production of monocrystalline silicon blocks. Than edges are sliced and blocks are sawn.
Geography	Text	Data for RER.
DataGeneratorAndPublication	Person	342,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	202,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	crystalline silicon
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	320,00
	Details	Passed.
	OtherDetails	none

Table 64: Metadata for single silicon wafers.

ReferenceFunction	Name	single-Si wafer, photovoltaics, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	m2
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	297,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Sawing and cleaning of wafers. The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific NOx- and waterborne pollutants are considered. No data on other process specific air emissions.
	Amount	1,00
	LocalName	Wafer, single-Si, Photovoltaik, ab Werk
	Synonyms	monocrystalline//single crystalline//silicon
	GeneralComment	The reference flow for the life cycle inventory is 1 square metre of wafer surface. The sc-Silicon columns are sawn into square wafers with a size 156x156 mm2 (0.0243 m2) and a thickness of 270 um. The weight is 629 g/m2.
	InfrastructureIncluded	1,00
	Category	photovoltaic
	SubCategory	production of components
	LocalCategory	Photovoltaik
	LocalSubCategory	Herstellung Komponenten
	Formula	
	StatisticalClassification	
	CASNumber	

TimePeriod	StartDate	1992
	EndDate	2006
	DataValidForEntirePeriod	1,00
	OtherPeriodText	Collection of data in 2005. Use of data from an environmental report for a production plant (ca. 3 million wafers per year) and some data from older publications.
Geography	Text	Europe, Western + North America
Technology	Text	Use of multi wire saws.
Representativeness	Percent	20,00
	ProductionVolume	7.5E5 m2 in 2005
	SamplingProcedure	Data collection by factory representatives. Environmental report and LCA studies.
	Extrapolations	Rough assumption for electricity use
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	342,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	202,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	wafer
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	320,00
	Details	Passed
	OtherDetails	none

Table 65: Metadata for photovoltaic cell.

ReferenceFunction	Name	photovoltaic cell, single-Si, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	m2
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	297,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Cleaning, damage etching, texture etching, covering of backside, phosphor dotation, phosphor glass etching, printing of contacts, cleaning and quality testing.
	Amount	1,00
	LocalName	Solarzelle, single-Si, ab Werk
	Synonyms	monocrystalline//single crystalline//silicon
	GeneralComment	Production of photovoltaic cells (156*156 mm2). Some inputs and emissions aggregated to protect sensitive data. Wafer thickness 270-300 um with an efficiency of 15.4% and 1.5Wp
	InfrastructureIncluded	1,00
	Category	photovoltaic
	SubCategory	production of components
	LocalCategory	Photovoltaik
	LocalSubCategory	Herstellung Komponenten
	Formula	
	StatisticalClassification	
	CASNumber	

TimePeriod	StartDate	2004
	EndDate	2005
	DataValidForEntirePeriod	1,00
	OtherPeriodText	Data investigated in 2004 and recalculated for the cell size in 2005.
Geography	Text	Data for production in Europe.
Technology	Text	Average production technology of photovoltaic cells from wafers.
Representativeness	Percent	6,00
	ProductionVolume	Total worldwide production 243MW in 2000. Europe 37MW.
	SamplingProcedure	Data collected from 5 specific processes and companies (4 multi-Si + 1 single-Si processing company).
	Extrapolations	Data 2005 calculated from data 2004 by multiplying amounts of materials by solar cell area factor of 156*156/(125*125) = 1.56; energy scaled linearly with cell side length.
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	342,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	202,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	Si solar cell
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	320,00
	Details	Passed.
	OtherDetails	none

Table 66: Metadata for front metallization paste.

Type	Field name			Type	Field name	
Reference Function	Name	metallization paste, front side, at plant		TimePeriod	StartDate	2006
Geography	Location	RER			EndDate	2006
Reference Function	InfrastructureProcess	0,00			DataValidForEntirePeriod	1,00
Reference Function	Unit	kg			OtherPeriodText	Data investigated in 2006.
DataSetInformation	Type	2,00		Geography	Text	Data for production in Europe.
	Version	2,10		Technology	Text	Assumption that production technology is similar as for solders.
	energyValues	0,00		Representativeness	Percent	
	LanguageCode	en			ProductionVolume	not known
	LocalLanguageCode	de			SamplingProcedure	Chemical composition of typical pastes taken from Material Safety Data Sheets.
DataEntryBy	Person	297,00			Extrapolations	Other data investigated with information from solder production.
	QualityNetwork	1,00			UncertaintyAdjustments	none
Reference Function	DataSetRelatesToProduct	1,00		DataGeneratorAndPublication	Person	342,00
	IncludedProcesses	Production of paste used in production of photovoltaic cells.			DataPublishedIn	2,00
	Amount	1,00			ReferenceToPublishedSource	202,00
	LocalName	Metallisierungspaste, Vorderseite, ab Werk			Copyright	1,00
	Synonyms				AccessRestrictedTo	0,00
	GeneralComment	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.			CompanyCode	
	InfrastructureIncluded	1,00			CountryCode	
	Category	photovoltaic			PageNumbers	Si solar cell
	SubCategory	production of components		DataSetInformation	ImpactAssessmentResult	1,00
	LocalCategory	Photovoltaik		ProofReading	Validator	320,00
	LocalSubCategory	Herstellung Komponenten			Details	Passed.
	Formula				OtherDetails	none
	StatisticalClassification					
	CASNumber					

Table 67: Metadata for back side metallization paste with aluminum.

Type	Field name			TimePeriod	StartDate	2006
ReferenceFunction	Name	metallization paste, back side, aluminium, at plant			EndDate	2006
Geography	Location	RER			DataValidForEntirePeriod	1,00
ReferenceFunction	InfrastructureProcess	0,00			OtherPeriodText	Data investigated in 2006.
ReferenceFunction	Unit	kg		Geography	Text	Data for production in Europe.
DataSetInformation	Type	2,00		Technology	Text	Assumption that production technology is similar as for solders.
	Version	2,10		Representativeness	Percent	
	energyValues	0,00			ProductionVolume	not known
	LanguageCode	en			SamplingProcedure	Chemical composition of typical pastes taken from Material Safety Data Sheets.
	LocalLanguageCode	de			Extrapolations	Other data investigated with information from solder production.
DataEntryBy	Person	297,00			UncertaintyAdjustments	none
	QualityNetwork	1,00		DataGeneratorAndPublication	Person	342,00
ReferenceFunction	DataSetRelatesToProduct	1,00			DataPublishedIn	2,00
	IncludedProcesses	Production of paste used in production of photovoltaic cells.			ReferenceToPublishedSource	202,00
	Amount	1,00			Copyright	1,00
	LocalName	Metallisierungspaste, Rückseite, Aluminium, ab Werk			AccessRestrictedTo	0,00
	Synonyms				CompanyCode	
	GeneralComment	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.			CountryCode	
	InfrastructureIncluded	1,00			PageNumbers	Si solar cell
	Category	photovoltaic		DataSetInformation	ImpactAssessmentResult	1,00
	SubCategory	production of components		ProofReading	Validator	320,00
	LocalCategory	Photovoltaik			Details	Passed.
	LocalSubCategory	Herstellung Komponenten			OtherDetails	none
	Formula					
	StatisticalClassification					
	CASNumber					

Table 68: Metadata for back side metallization paste.

Type	Field name	
ReferenceFunction	Name	metallization paste, back side, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	kg
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	297,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Production of paste used in production of photovoltaic cells.
	Amount	1,00
	LocalName	Metallisierungspaste, Rückseite, ab Werk
	Synonyms	
	GeneralComment	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.
	InfrastructureIncluded	1,00
	Category	photovoltaic
	SubCategory	production of components
	LocalCategory	Photovoltaik
	LocalSubCategory	Herstellung Komponenten
	Formula	
	StatisticalClassification	
	CASNumber	

TimePeriod	StartDate	2006
	EndDate	2006
	DataValidForEntirePeriod	1,00
	OtherPeriodText	Data investigated in 2006.
Geography	Text	Data for production in Europe.
Technology	Text	Assumption that production technology is similar as for solders.
Representativeness	Percent	
	ProductionVolume	not known
	SamplingProcedure	Chemical composition of typical pastes taken from Material Safety Data Sheets.
	Extrapolations	Other data investigated with information from solder production.
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	342,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	202,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	Si solar cell
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	320,00
	Details	Passed.
	OtherDetails	none

Table 69: Metadata for inverter, 2 400 W.

Type	Field name	
ReferenceFunction	Name	inverter, 2500W, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	1
ReferenceFunction	Unit	unit
DataSetInformation	Type	2
	Version	2,1
	energyValues	0
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	337
	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
	IncludedProcesses	Materials, packaging and electricity use for the production of an inverse rectifier. Disposal of the product after use.
	Amount	1
	LocalName	Wechselrichter, 2500W, ab Werk
	Synonyms	inverse rectifier
	GeneralComment	Production of an inverter (2500W) with an efficiency of 93.5% (total efficiency factor which includes MPP-Tracking) for photovoltaic plant. Total weight about 18.5 kg.
	InfrastructureIncluded	1
	Category	photovoltaic
	SubCategory	production of components
	LocalCategory	Photovoltaik
	LocalSubCategory	Herstellung Komponenten
	Formula	
	StatisticalClassification	
	CASNumber	

Type	Field name	
ReferenceFunction	Name	inverter, 2500W, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	1
ReferenceFunction	Unit	unit
TimePeriod	StartDate	2004
	EndDate	2006
	DataValidForEntirePeriod	1
	OtherPeriodText	
Geography	Text	Production in RER.
Technology	Text	Inverter for a photovoltaic grid-connected system with a capacity of 2.5kWp.
Representativeness	Percent	
	ProductionVolume	Not known.
	SamplingProcedure	Detailed analysis of materials for one product
	Extrapolations	Data for electronic components has been extrapolated from 500 W-
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	337
	DataPublishedIn	2
	ReferenceToPublishedSource	202
	Copyright	1
	AccessRestrictedTo	0
	CompanyCode	
	CountryCode	
	PageNumbers	
DataSetInformation	ImpactAssessmentResult	1
ProofReading	Validator	318
	Details	passed
	OtherDetails	none

Table 70: Metadata for electric installation.

Type	Field name			TimePeriod	StartDate	1992
ReferenceFunction	Name	electric installation, photovoltaic plant, at plant			EndDate	1992
Geography	Location	CH			DataValidForEntirePeriod	1,00
ReferenceFunction	InfrastructureProcess	1,00			OtherPeriodText	Date of data investigation.
ReferenceFunction	Unit	unit		Geography	Text	Production in CH.
DataSetInformation	Type	2,00		Technology	Text	All electric installations for a photovoltaic system with a capacity of 3kWp. Including cables, counter, etc.
	Version	2,10		Representativeness	Percent	5,00
	energyValues	0,00			ProductionVolume	Not known.
	LanguageCode	en			SamplingProcedure	Detailed analysis of materials for one product in a diploma thesis.
	LocalLanguageCode	de			Extrapolations	none
DataEntryBy	Person	297,00			UncertaintyAdjustments	none
	QualityNetwork	1,00		DataGeneratorAndPublication	Person	297,00
ReferenceFunction	DataSetRelatesToProduct	1,00			DataPublishedIn	2,00
	IncludedProcesses	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use.			ReferenceToPublishedSource	202,00
	Amount	1,00			Copyright	1,00
	LocalName	Elektroinstallationen, Photovoltaikanlage, ab Werk			AccessRestrictedTo	0,00
	Synonyms				CompanyCode	
	GeneralComment	Production of different components of the electric installation for a 3kWp photovoltaic plant.			CountryCode	
	InfrastructureIncluded	1,00			PageNumbers	BOS
	Category	photovoltaic		DataSetInformation	ImpactAssessmentResult	1,00
	SubCategory	production of components		ProofReading	Validator	320,00
	LocalCategory	Photovoltaik			Details	Passed.
	LocalSubCategory	Herstellung Komponenten			OtherDetails	none
	Formula					
	StatisticalClassification					
	CASNumber					

Table 71: Metadata for roof installation.

Type	Field name				
ReferenceFunction	Name	slanted-roof construction, mounted, on roof	TimePeriod	StartDate	1992
				EndDate	2008
Geography	Location	RER		DataValidForEntirePeriod	1,00
ReferenceFunction	InfrastructureProcess	1,00		OtherPeriodText	Date of data investigation. Actual weight of materials updated in 2008.
ReferenceFunction	Unit	m2	Geography	Text	Production in CH.
DataSetInformation	Type	2,00	Technology	Text	Construction parts for a photovoltaic system.
	Version	2,10	Representativeness	Percent	10,00
	energyValues	0,00		ProductionVolume	Not known.
	LanguageCode	en		SamplingProcedure	Detailed analysis of materials for one product in a diploma thesis.
	LocalLanguageCode	de		Extrapolations	From one product to the whole market. Correction factor applied to correct for today average weight per m2.
DataEntryBy	Person	297,00		UncertaintyAdjustments	none
	QualityNetwork	1,00	DataGeneratorAndPublication	Person	297,00
ReferenceFunction	DataSetRelatesToProduct	1,00		DataPublishedIn	2,00
	IncludedProcesses	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.		ReferenceToPublishedSource	207,00
	Amount	1,00		Copyright	1,00
	LocalName	Schrägdachkonstruktion, aufgesetzt, auf Dach		AccessRestrictedTo	0,00
	Synonyms			CompanyCode	
	GeneralComment	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.		CountryCode	
	InfrastructureIncluded	1,00		PageNumbers	BOS
	Category	photovoltaic	DataSetInformation	ImpactAssessmentResult	1,00
	SubCategory	production of components	ProofReading	Validator	318,00
	LocalCategory	Photovoltaik		Details	Passed.
	LocalSubCategory	Herstellung Komponenten		OtherDetails	none
	Formula				
	StatisticalClassification				
	CASNumber				

Table 72: Metadata for AR-coating.

ReferenceFunction	Name	anti-reflex-coating, etching, solar glass	TimePeriod	StartDate	2002
Geography	Location	DK		EndDate	2002
ReferenceFunction	InfrastructureProcess	0,00E+00		DataValidForEntirePeriod	1,00E+00
ReferenceFunction	Unit	m2		OtherPeriodText	Time of information
DataSetInformation	Type	2,00E+00	Geography	Text	Production plant in DK. Some pre-products and waste treatment services estimated with European and Swiss data.
	Version	2,10E+00		SamplingProcedure	Personal communication
	energyValues	0,00E+00	Representativeness	Percent	1,00E+02
	LanguageCode	en		ProductionVolume	One company. Capacity 175000m² per shift * year or 400000-500000m² per year
	LocalLanguageCode	de		CompanyCode	
DataEntryBy	Person	2,97E+02		Extrapolations	
	QualityNetwork	1,00E+00		UncertaintyAdjustments	none
ReferenceFunction	DataSetRelatesToProduct	1,00E+00	DataGeneratorAndPublication	Person	2,97E+02
	IncludedProcesses	Gate to gate inventory for the process including cleaning, etching and clarification and drying. Losses of glass are not included.		DataPublishedIn	2,00E+00
	Amount	1,00E+00		ReferenceToPublishedSource	1,38E+02
	LocalName	Antireflexbeschichten, Ätzen, Solarglas		Copyright	1,00E+00
	Synonyms			AccessRestrictedTo	0,00E+00
	GeneralComment	The filter cake contains silicone-sodium-fluoride and calcium carbonates or oxides. They can be disposed with the normal household wastes. Standard distances have been assumed for the transport. The exhausts from the treatment chambers go through a so-called air-scrubber (air/water cleaner). The waste material from the scrubber is collected with the water from rinsing of the glasses between the different operations of the treatment and from the final cleaning. This liquid is then passed through a waste water treatment system, resulting in clean water, to be used again in process. The dry matters from the filter press consist of non-aggressive and non-toxic materials, mainly silica-, sodium-, fluoride- and calcium- carbonates and oxides	Technology	Text	The antireflection microstructure is impressed on the solar glass by an automatic etching procedure. Etching is made with fluorosilic acid (H2(SiF6). It is possible to produce a film layer on structured and smooth float glass as well as on tempered or un-tempered glasses.
	InfrastructureIncluded	1,00E+00		CountryCode	
	Category	glass		PageNumbers	Glass Products and Processing
	SubCategory	construction	DataSetInformation	ImpactAssessmentResult	1,00E+00
	LocalCategory	Glas	ProofReading	Validator	2,83E+02
	LocalSubCategory	Bauglas		Details	Passed.
	Formula			OtherDetails	
	StatisticalClassification				
	CASNumber				

Table 73: Metadata for encapsulate.

Type	Field name		TimePeriod	StartDate	1993
ReferenceFunction	Name	ethylvinylacetate, foil, at plant		EndDate	1997
Geography	Location	RER		DataValidForEntirePeriod	1,00
ReferenceFunction	InfrastructureProcess	0,00		OtherPeriodText	time to which data refer
ReferenceFunction	Unit	kg	Geography	Text	based on average European extrusion
DataSetInformation	Type	2,00	Representativeness	Percent	
	Version	2,10		ProductionVolume	unknown
	energyValues	0,00		SamplingProcedure	company data
	LanguageCode	en		Extrapolations	no extrapolation
	LocalLanguageCode	de		UncertaintyAdjustments	none
DataEntryBy	Person	294,00	DataGeneratorAndPublication	Person	294,00
	QualityNetwork	1,00		DataPublishedIn	2,00
ReferenceFunction	DataSetRelatesToProduct	1,00		ReferenceToPublishedSource	142,00
	IncludedProcesses	This process contains the plastic amount and the transport of the plastic from the production site to the converting site as well as the dataset "extrusion, plastic film"		Copyright	1,00
	Amount	1,00		AccessRestrictedTo	0,00
	LocalName	Ethyl-Vinylacetat-, Folie, ab Werk		CompanyCode	
	Synonyms			CountryCode	
	GeneralComment	Example process for the utilization of the different converting modules in the database.		PageNumbers	
Technology	Text	present technologies	DataSetInformation	ImpactAssessmentResult	1,00
	InfrastructureIncluded	1,00	ProofReading	Validator	285,00
	Category	plastics		Details	passed
	SubCategory	polymers		OtherDetails	
	LocalCategory	Kunststoffe			
	LocalSubCategory	Polymere (Granulate)			
	Formula				
	StatisticalClassification				
	CASNumber				

Table 74: Metadata for front and back glass.

ReferenceFunction	Name	flat glass, uncoated, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	kg
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	285,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Includes the whole manufacturing process to produce flat glass (raw material provision, cullet addition, melting process, forming process (on float bath), cooling process (annealing lehr), cutting process and storage), internal processes (transport, etc.) and infrastructure. No administration and packing is included.
	Amount	1,00
	LocalName	Flachglas, unbeschichtet, ab Werk
	Synonyms	plate//float//Flach
	GeneralComment	The amount of raw materials is calculated based on the composition of flat glass. The total amount of energy is partitioned in 58% from natural gas, 38% heavy fuel oil and 5% electrical. The amount of tin yearly added to the tin bath is assumed to leave the system by air, as part of the particulates. The same with lead. Both emissions are double counted: as particulate and as emission to air. Most other emissions are a mean value of plants with and plants without abatment. It is assumed that half of water evaporates and other half is treated.

	InfrastructureIncluded	1,00
	Category	glass
	SubCategory	construction
	LocalCategory	Glas
	LocalSubCategory	Bauglas
	Formula	
	StatisticalClassification	
	CASNumber	
TimePeriod	StartDate	1996
	EndDate	2001
	DataValidForEntirePeriod	1,00
	OtherPeriodText	
Technology	Text	Basic principle is pouring molten glass onto a bath of molten tin and forming a ribbon with the upper and lower surfaces becoming parallel under the influence of gravity and surface tension. Average technique used in European flat glas production.
Geography	Text	For some exchanges CH- and DE-modules have been used as proxy
Representativeness	Percent	
	ProductionVolume	unknown
	SamplingProcedure	Literature
	Extrapolations	See geography
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	283,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	138,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	320,00
	Details	passed
	OtherDetails	

Table 75: Metadata for protective back sheet.

Type	Field name	
ReferenceFunction	Name	polyethylene, HDPE, granulate, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0,00
ReferenceFunction	Unit	kg
DataSetInformation	Type	2,00
	Version	2,10
	energyValues	0,00
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	294,00
	QualityNetwork	1,00
ReferenceFunction	DataSetRelatesToProduct	1,00
	IncludedProcesses	Aggregated data for all processes from raw material extraction until delivery at plant
	Amount	1,00
	LocalName	Polyethylen-Granulat, HDPE, ab Werk
	Synonyms	HDPE//PE//HD-PE
	InfrastructureIncluded	1,00
	Category	plastics
	SubCategory	polymers
	LocalCategory	Kunststoffe
	LocalSubCategory	Polymere (Granulate)
	Formula	
	StatisticalClassification	
	GeneralComment	Data are from the Eco-profiles of the European plastics industry (PlasticsEurope). Not included are the values reported for: recyclable wastes, amount of air / N2 / O2 consumed, unspecified metal emission to air and to water, mercaptan emission to air, unspecified CFC/HCFC emission to air, dioxin to water. The amount of "sulphur (bonded)" is assumed to be included into the amount of raw oil.

	CASNumber	009002-88-4
TimePeriod	StartDate	1999
	EndDate	2001
	DataValidForEntirePeriod	1,00
	OtherPeriodText	time to which data refer
Geography	Text	24 European production sites
Technology	Text	polymerization out of ethylene under normal pressure and temperature
Representativeness	Percent	
	ProductionVolume	4.31 Mt (1999)
	SamplingProcedure	literature values based on company survey
	Extrapolations	no extrapolations
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	294,00
	DataPublishedIn	2,00
	ReferenceToPublishedSource	142,00
	Copyright	1,00
	AccessRestrictedTo	0,00
	CompanyCode	
	CountryCode	
	PageNumbers	
DataSetInformation	ImpactAssessmentResult	1,00
ProofReading	Validator	331,00
	Details	passed.
	OtherDetails	

Table 76: Metadata for transport with freight ship.

ReferenceFunction	Name	transport, transoceanic freight ship	TimePeriod	StartDate	1992
Geography	Location	OCE		EndDate	2000
ReferenceFunction	InfrastructureProcess	0		DataValidForEntirePeriod	1
ReferenceFunction	Unit	tkm		OtherPeriodText	
DataSetInformation	Type	2	Geography	Text	Data from one port in Netherlands is employed as an estimate for international water transportation.
	Version	2,1	Technology	Text	HFE based steam turbine and diesel engines.
	energyValues	0	Representativeness	Percent	0
	LanguageCode	en		ProductionVolume	
	LocalLanguageCode	de		SamplingProcedure	National statistics, literature studies
DataEntryBy	Person	305		Extrapolations	see geography
	QualityNetwork	1		UncertaintyAdjustments	none
ReferenceFunction	DataSetRelatesToProduct	1	DataGeneratorAndPublication	Person	305
	IncludedProcesses	The module calls the modules addressing: operation of vessel; production of vessel; construction and land use of port; operation, maintenance and disposal of port.		DataPublishedIn	2
	Amount	1		ReferenceToPublishedSource	145
	LocalName	Transport, Frachter Übersee		Copyright	1
	Synonyms			AccessRestrictedTo	0
	GeneralComment	Inventory refers to the entire transport life cycle. Port infrastructure expenditures and environmental interventions are allocated based the yearly throughput (0.37). Vessel manufacturing is allocated based on the total kilometric performance (2'000'000km) and its transport performance (50000/unit). For each transport activity 2 ports are required.		CompanyCode	
	Category	transport systems		CountryCode	
	SubCategory	ship		PageNumbers	water transport
	LocalCategory	Transportsysteme	DataSetInformation	ImpactAssessmentResult	1
	LocalSubCategory	Wasser	ProofReading	Validator	297
	Formula			Details	passed.
	StatisticalClassification			OtherDetails	
	CASNumber				

Table 77: Metadata for transport with lorry 16-32 tons, EURO 5.

Type	Field name	
ReferenceFunction	Name	transport, lorry 16-32t, EURO5
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	tkm
DataSetInformation	Type	2
	Version	2,1
	energyValues	0
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	334
	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
	IncludedProcesses	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.
	Amount	1
	LocalName	Transport, Lkw 16-32t, EURO5
	Synonyms	
	GeneralComment	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 540000 vkm/vehicle has been assumed.
	InfrastructureIncluded	1
	Category	transport systems
	SubCategory	road
	LocalCategory	Transportsysteme
	LocalSubCategory	Strasse
	Formula	
	StatisticalClassification	
	CASNumber	

TimePeriod	StartDate	2005
	EndDate	2005
	DataValidForEntirePeriod	1
	OtherPeriodText	
Geography	Text	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.
Technology	Text	Diesel
Representativeness	Percent	100
	ProductionVolume	not known
	SamplingProcedure	Literature data.
	Extrapolations	none
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	334
	DataPublishedIn	0
	ReferenceToPublishedSource	145
	Copyright	1
	AccessRestrictedTo	0
	CompanyCode	
	CountryCode	
	PageNumbers	
DataSetInformation	ImpactAssessmentResult	1
ProofReading	Validator	339
	Details	passed
	OtherDetails	

Table 78: Metadata for transport with lorry 3,5 - 7,5 tons, EURO 5.

Type	Field name	
ReferenceFunction	Name	transport, lorry 3.5-7.5t, EURO5
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	tkm
DataSetInformation	Type	2
	Version	2,1
	energyValues	0
	LanguageCode	en
	LocalLanguageCode	de
DataEntryBy	Person	334
	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
	IncludedProcesses	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.
	Amount	1
	LocalName	Transport, Lkw 3.5-7.5t, EURO5
	Synonyms	
	GeneralComment	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 540000 vkm/vehicle has been assumed.
	InfrastructureIncluded	1
	Category	transport systems
	SubCategory	road
	LocalCategory	Transportsysteme
	LocalSubCategory	Strasse
	Formula	
	StatisticalClassification	
	CASNumber	

TimePeriod	StartDate	2005
	EndDate	2005
	DataValidForEntirePeriod	1
	OtherPeriodText	
Technology	Text	Diesel
Representativeness	Percent	100
	ProductionVolume	not known
	SamplingProcedure	Literature data.
	Extrapolations	none
	UncertaintyAdjustments	none
DataGeneratorAndPublication	Person	334
	DataPublishedIn	0
	ReferenceToPublishedSource	145
	Copyright	1
	AccessRestrictedTo	0
	CompanyCode	
	CountryCode	
Geography	Text	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.
	PageNumbers	
DataSetInformation	ImpactAssessmentResult	1
ProofReading	Validator	339
	Details	passed
	OtherDetails	

Appendix 5, impact categories result, resources, degradation and production data

Table 79: Results from impact categories by process per function unit for 30 years PV system lifetime.

	Panel							BOS			
	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport		Inverter	Electric installation	roof installation	Transport
Global Warming Potential, 100 years	0,0378957	0,00063854	0,000243277	0,00041068	3,186E-06	0,00061901		0,00475681	0,001644441	0,00681147	0,0002491
Acidification Potential	0,0001364	2,0443E-06	8,43359E-07	2,1208E-06	1,067E-08	2,609E-06		4,3553E-05	2,43148E-05	2,7608E-05	7,383E-07
Eutrophication Potential	8,39E-05	1,2825E-06	1,37088E-06	8,3489E-07	6,371E-09	3,0699E-06		1,9659E-05	7,69357E-06	1,7605E-05	1,01E-06
Ozon Depletion Potential, 10 years	2,112E-08	3,8137E-11	2,97072E-11	5,6409E-11	1,094E-15	8,4924E-11		5,2868E-10	4,99717E-11	5,3944E-10	3,502E-11
Human Toxicity Potential, 100 years	0,0109627	0,00013491	0,000620922	8,7536E-05	1,677E-08	0,0001124		0,01874178	0,013952376	0,04082123	3,633E-05
Ionizing Radiation Potential	2,025E-11	3,0563E-12	8,80501E-12	9,5593E-13	4,561E-17	1,3103E-12		4,6096E-11	6,55354E-12	6,109E-11	6,004E-13
Water	0,865229	0,00607113	0,047197191	0,00851886	5,634E-06	0,00256434		0,06014446	0,01235107	0,05374349	0,0009812
Land	0,001157	4,861E-05	0,000198277	6,3251E-05	3,557E-10	1,015E-05		0,00040384	4,55181E-05	0,00036616	5,161E-06
Resources	0,0013084	0,00049807	0,000795053	0,00018964	2,61E-06	0,0003321		0,00300342	0,000786311	0,00249345	0,0001014
Cumulative Energy Demand	0,2240758	0,00603001	0,000908761	0,00192716	3,511E-05	0,00452021		0,02453198	0,007667906	0,03691865	0,0010806
Renewable Energy	0,0336112	0,00017516	2,45063E-05	0,00019878	4,083E-07	6,6853E-05		0,00179617	0,000388049	0,00567476	1,654E-05
Non-Renewable Energy	0,1904646	0,00585484	0,000884254	0,00172838	3,47E-05	0,00445336		0,02273581	0,007279858	0,03124389	0,0010641

Table 80: Results from impact categories by process per function unit for 40 years PV system lifetime.

	Panel							BOS			
	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport		Inverter	Electric installation	roof installation	Transport
Global Warming Potential, 100 years	0,0291218	0,0004907	0,000186951	0,00031559	2,448E-06	0,00047569		0,003655474	0,001263706	0,00523442	0,0001914
Acidification Potential	0,0001049	1,571E-06	6,48097E-07	1,6298E-06	8,202E-09	2,00498E-06		3,34694E-05	1,86852E-05	2,1216E-05	5,674E-07
Eutrophication Potential	6,448E-05	9,9324E-07	1,05349E-06	6,4159E-07	4,896E-09	2,35912E-06		1,51073E-05	5,91229E-06	1,3529E-05	7,76E-07
Ozon Depletion Potential, 10 years	1,623E-08	2,9307E-11	2,28291E-11	4,3349E-11	8,408E-16	6,52617E-11		4,06278E-10	3,84019E-11	4,1454E-10	2,691E-11
Human Toxicity Potential, 100 years	0,0084245	0,00010367	0,000477161	6,7269E-05	1,289E-08	8,63751E-05		0,014402523	0,010722003	0,03136995	2,792E-05
Ionizing Radiation Potential	1,556E-11	2,3487E-12	6,7664E-12	7,346E-13	3,505E-17	1,00695E-12		3,54232E-11	5,03621E-12	4,6946E-11	4,614E-13
Water	0,0006649	0,00466549	0,036269695	0,0065465	4,33E-06	0,001970625		0,046219303	0,009491445	0,04130034	0,000754
Land	0,0008891	3,7355E-05	0,00015237	4,8606E-05	2,734E-10	7,79983E-06		0,000310337	3,49794E-05	0,00028138	3,966E-06
Resources	0,0010055	0,00038275	0,000610975	0,00014574	2,006E-06	0,000255208		0,002308045	0,000604258	0,00191615	7,794E-05
Cumulative Energy Demand	0,1721958	0,00463389	0,000698357	0,00148097	2,698E-05	0,003473653		0,018852127	0,005892567	0,02837093	0,0008304
Renewable Energy	0,0258292	0,00013461	1,88324E-05	0,00015276	3,137E-07	5,13744E-05		0,001380302	0,000298204	0,00436089	1,271E-05
Non-Renewable Energy	0,1463666	0,00449928	0,000679524	0,00132821	2,667E-05	0,003422279		0,017471824	0,005594363	0,02401004	0,0008177

Table 81: Results from impact categories by process per FU during 30 years for total amount of solar cells.

	Sand	MG silicon	SoG silicon(siemens)	silicon prod. mix	CZ mono-Si	Wafer sawing	cell production	Metallization paste front	Metallization paste back contact	Metallization paste back, alluminium
GWP, kg CO2-Eq	1,8318E-05	0,001611	0,009963	0,001729	0,015486	0,006544	0,007363	0,000146	7,53E-05	0,000173
AP, kg SO2-Eq	4,9955E-08	9E-06	1,58E-05	1,92E-06	6,53E-05	2,65E-05	3,31E-05	3,24E-06	1,66E-06	7,97E-07
EO, kg NOx-Eq	4,4607E-08	5,71E-06	2,2E-05	3,45E-06	3,14E-05	1,51E-05	1,7E-05	2,01E-06	1,03E-06	3,61E-07
ODP, kg CFC-11-Eq	2,2787E-12	9,18E-11	2,82E-09	9,74E-10	1,4E-09	9,24E-10	1,58E-08	1,21E-11	6,25E-12	1,13E-11
Human Toxicity Potential 100a	3,1966E-06	0,000195	0,000529	0	0,002414	0,004735	0,003809	0,001133	0,00058	0,000723
ionising radiation, DALY/kWh	6,9025E-07	0,00021	0,000395	0	0,01031	0,003097	0,004695	3,83E-13	1,98E-13	9,57E-13
Water, m3/kWh	3,504E-07	4E-06	1,17E-05	1,01E-06	0,000615	0,000103	0,000126	2,15E-06	1,1E-06	7,52E-07
Land, m2a/kWh	7,5864E-07	0,000329	7,05E-05	0	0,000234	0,000344	0,00016	1,04E-05	5,32E-06	2,55E-06
Resources kg/kWh	1,6786E-06	0,000595	0,002923	0,000476	0,008258	0,003862	0,004029	7,18E-05	3,7E-05	8,93E-05
CED, kWh/kWh	2,1613E-05	0,009179	0,053253	0,006246	0,078537	0,036587	0,038537	0,0006	0,00031	0,000806

Table 82: Results from impact categories by process per function unit for 180 micrometer thick solar cells.

	Panel							BOS			
	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport		Inverter	Electric installation	roof installation	Transport
Global Warming Potential, 100 years	0,0334882	0,00063854	0,000243277	0,00041068	3,186E-06	0,000619008	0	0,004756812	0,001644441	0,00681147	0,0002491
Acidification Potential	0,0001266	2,0443E-06	8,43359E-07	2,1208E-06	1,067E-08	2,60905E-06	0	4,35532E-05	2,43148E-05	2,7608E-05	7,383E-07
Eutrophication Potential	7,726E-05	1,2925E-06	1,37088E-06	8,3489E-07	6,371E-09	3,06989E-06	0	1,96588E-05	7,69357E-06	1,7605E-05	1,01E-06
Ozon Depletion Potential, 10 years	1,844E-08	3,8137E-11	2,97072E-11	5,6409E-11	1,094E-15	8,4924E-11	0	5,28684E-10	4,99717E-11	5,3944E-10	3,502E-11
Human Toxicity Potential, 100 years	0,013073	0,00013491	0,000620922	8,7536E-05	1,677E-08	0,000112399	0	0,01874178	0,013952376	0,04082123	3,633E-05
Ionizing Radiation Potential	1,66E-11	3,0563E-12	8,80501E-12	9,5593E-13	4,561E-17	1,31033E-12	0	4,60956E-11	6,55354E-12	6,109E-11	6,004E-13
Water	0,0006543	0,00607113	0,047197191	0,00851886	5,634E-06	0,002564344	0	0,060144461	0,01235107	0,05374349	0,0009812
Land	0,000945	4,861E-05	0,000198277	6,3251E-05	3,557E-10	1,01498E-05	0	0,000403837	4,55181E-05	0,00036616	5,161E-06
Resources	0,0081669	0,00049807	0,000795053	0,00018964	2,61E-06	0,000332098	0	0,003003423	0,000786311	0,00249345	0,0001014
Cumulative Energy Demand	0,1740152	0,00603001	0,000908761	0,00192716	3,511E-05	0,004520211	0	0,024531979	0,007667906	0,03691865	0,0010806
Renewable Energy	0,0245736	0,00017516	2,45063E-05	0,00019878	4,083E-07	6,68527E-05	0	0,001796166	0,000388049	0,00567476	1,654E-05
Non-Renewable Energy	0,1494303	0,00585484	0,000884254	0,00172838	3,47E-05	0,004453358	0	0,022735813	0,007279858	0,03124389	0,0010641

Table 83: Recourses for PV system per function unit for 30 years lifetime.

	Panel							BOS			
	Solar cells	Encapsula	Front and	AR-coatin	Protective back sheet	transport		Inverter	Electric installati	roof installation	transport
NRR, aluminium	1,73E-05	2,21E-07	7,5E-07	2,2E-07	4,8442E-12	4,90E-07		1,99E-05	1,05806E-06	0,000315071	1,52E-07
NRR, antimony	1,98E-12	9,49E-16	2,04E-15	3,3E-16	2,59215E-20	5,48E-14		1,09E-14	1,4693E-15	1,60982E-14	2,14E-14
NRR, brown coal	0,000463	6,57E-05	8,63E-05	1,64E-05	7,55964E-10	1,71E-05		0,001004	0,000143157	0,00043185	4,88E-06
NRR, cadmium	1,39E-10	3,1E-11	9,52E-11	1,25E-11	7,66723E-16	1,68E-09		3,07E-10	3,69822E-11	8,42126E-10	4,90E-10
NRR, coal	0,000318	4,98E-05	0,000141	8,67E-05	1,67632E-07	2,99E-05		0,000843	0,000128775	0,000725406	8,61E-06
NRR, cobalt	1,08E-12	1,45E-13	7,53E-13	8,41E-14	3,83729E-17	5,30E-12		3,34E-11	3,39137E-13	1,1092E-11	1,77E-12
NRR, copper	9,73E-07	2,03E-07	6,09E-07	1,89E-07	2,21117E-12	1,26E-07		0,000121	0,000106617	5,56242E-06	3,94E-08
NRR, gold	6,17E-12	1,38E-11	1,93E-11	2,04E-12	9,9649E-17	1,42E-11		8,79E-09	2,9416E-12	1,08174E-11	4,40E-12
NRR, iron	2,98E-05	2,99E-06	8,71E-06	3,28E-06	3,55491E-10	2,45E-05		0,000277	1,46339E-05	0,000423076	7,01E-06
NRR, lead	8,45E-08	2,83E-09	6,52E-09	8,07E-09	9,01424E-13	1,41E-07		5,41E-07	4,46644E-09	2,51623E-07	5,52E-08
NRR, manganese	3,24E-07	1,86E-08	3,21E-08	6,1E-09	6,80405E-13	1,58E-08		3,69E-06	1,44398E-07	5,84287E-06	4,25E-09
NRR, mercury	6,76E-11	9E-13	1,07E-12	7,49E-13	4,3347E-15	1,06E-12		6,24E-11	9,50865E-12	1,70871E-10	3,40E-13
NRR, molybdenum	7,52E-08	4,01E-09	1E-08	2,99E-09	4,28286E-14	2,39E-09		2,02E-06	1,57619E-06	2,73676E-07	7,25E-10
NRR, natural gas	0,000343	0,00015	0,000316	7,14E-05	9,56037E-07	2,12E-05		0,000405	0,000166095	0,000192716	6,61E-06
NRR, nickel	1,97E-06	4,29E-07	5,66E-07	1,19E-07	4,05346E-12	2,22E-07		2,02E-05	3,90088E-06	2,26655E-05	6,15E-08
NRR, oil	0,000132	0,000229	0,000241	1,1E-05	1,48536E-06	2,38E-04		0,000303	0,000219739	0,000370516	7,40E-05
NRR, palladium	6,92E-13	6,2E-13	1,68E-12	1,4E-13	9,04891E-18	1,23E-12		3,37E-12	2,9379E-13	4,7878E-12	3,82E-13
NRR, platinum	1,81E-13	1,63E-14	4,89E-14	4,03E-14	3,29427E-19	3,25E-14		2,37E-13	3,38756E-14	2,3112E-13	1,06E-14
NRR, silver	1,82E-06	3,71E-11	5,19E-11	5,55E-12	2,69255E-16	3,80E-11		3,12E-07	8,41106E-12	3,07062E-11	1,18E-11
NRR, tantalum	6,45E-12	1,35E-11	1,88E-11	2,01E-12	9,75201E-17	1,38E-11		5,68E-07	3,01336E-12	1,1014E-11	4,28E-12
NRR, tin	7,62E-10	5,94E-10	1,74E-07	1,4E-10	6,0658E-15	6,78E-10		1,45E-06	4,2949E-10	1,33194E-09	2,06E-10
NRR, zinc	1,61E-07	7,54E-08	2,32E-07	3,08E-07	2,53018E-11	9,83E-08		3,03E-06	5,93284E-07	1,57359E-07	2,92E-08
RR, wood	8,49E-08	3,55E-08	4,7E-08	3,66E-08	8,99266E-14	2,35E-09		1,86E-07	1,65075E-08	5,99893E-08	7,21E-10

Table 84: Recourses for PV system per function unit for 40 years lifetime.

	Panel							BOS			
	Solar cells	Encapsula	Front and	AR-coatin	Protective back sheet	transport		Inverter	Electric installati	roof installation	transport
NRR, aluminium	2,25664E-05	2,88E-07	9,76E-07	2,87E-07	6,30368E-12	6,37688E-07	0	2,58E-05	1,37684E-06	0,000409997	1,97E-07
NRR, antimony	2,57687E-12	1,23E-15	2,65E-15	4,29E-16	3,37313E-20	7,12817E-14	0	1,42E-14	1,91197E-15	2,09484E-14	2,79E-14
NRR, brown coal	0,00060269	8,55E-05	0,000112	2,13E-05	9,83724E-10	2,22524E-05	0	0,001306	0,000186288	0,000561959	6,35E-06
NRR, cadmium	1,80473E-10	4,03E-11	1,24E-10	1,63E-11	9,97725E-16	2,1875E-09	0	3,99E-10	4,81243E-11	1,09585E-09	6,38E-10
NRR, coal	0,000413916	6,48E-05	0,000183	0,000113	2,18137E-07	3,89462E-05	0	0,001097	0,000167573	0,00094396	1,12E-05
NRR, cobalt	1,40453E-12	1,88E-13	9,8E-13	1,09E-13	4,99341E-17	6,90016E-12	0	4,34E-11	4,41313E-13	1,44339E-11	2,3E-12
NRR, copper	1,26596E-06	2,65E-07	7,92E-07	2,46E-07	2,87736E-12	1,63685E-07	0	0,000158	0,000138739	7,23829E-06	5,12E-08
NRR, gold	8,02586E-12	1,8E-11	2,52E-11	2,65E-12	1,29672E-16	1,84964E-11	0	1,14E-08	3,82786E-12	1,40765E-11	5,73E-12
NRR, iron	3,88322E-05	3,89E-06	1,13E-05	4,27E-06	4,62595E-10	3,18995E-05	0	0,00036	1,90429E-05	0,000550542	9,12E-06
NRR, lead	1,10001E-07	3,68E-09	8,49E-09	1,05E-08	1,17301E-12	1,84104E-07	0	7,04E-07	5,81211E-09	3,27433E-07	7,18E-08
NRR, manganese	4,2098E-07	2,42E-08	4,18E-08	7,94E-09	8,85401E-13	2,05911E-08	0	4,8E-06	1,87903E-07	7,60324E-06	5,53E-09
NRR, mercury	8,79587E-11	1,17E-12	1,39E-12	9,75E-13	5,64067E-15	1,37388E-12	0	8,11E-11	1,23735E-11	2,22352E-10	4,42E-13
NRR, molybdenum	9,78149E-08	5,22E-09	1,31E-08	3,89E-09	5,57322E-14	3,11067E-09	0	2,62E-06	2,05107E-06	3,5613E-07	9,44E-10
NRR, natural gas	0,000446166	0,000195	0,000411	9,3E-05	1,24408E-06	2,76219E-05	0	0,000527	0,000216137	0,000250778	8,6E-06
NRR, nickel	2,55765E-06	5,59E-07	7,36E-07	1,54E-07	5,2747E-12	2,89221E-07	0	2,63E-05	5,07616E-06	2,94943E-05	8,01E-08
NRR, oil	0,000171354	0,000298	0,000313	1,43E-05	1,93287E-06	0,000310001	0	0,000394	0,000285943	0,000482146	9,63E-05
NRR, palladium	9,0055E-13	8,07E-13	2,19E-12	1,82E-13	1,17752E-17	1,59976E-12	0	4,39E-12	3,82304E-13	6,23029E-12	4,97E-13
NRR, platinum	2,35721E-13	2,12E-14	6,37E-14	5,24E-14	4,28678E-19	4,23395E-14	0	3,09E-13	4,40818E-14	3,00753E-13	1,38E-14
NRR, silver	2,36705E-06	4,83E-11	6,76E-11	7,22E-12	3,50377E-16	4,94949E-11	0	4,07E-07	1,09452E-11	3,99575E-11	1,53E-11
NRR, tantalum	8,39627E-12	1,75E-11	2,45E-11	2,61E-12	1,26901E-16	1,79589E-11	0	7,39E-07	3,92123E-12	1,43323E-11	5,56E-12
NRR, tin	9,91853E-10	7,72E-10	2,26E-07	1,82E-10	7,89333E-15	8,82433E-10	0	1,89E-06	5,58889E-10	1,73323E-09	2,68E-10
NRR, zinc	2,09455E-07	9,81E-08	3,02E-07	4E-07	3,29249E-11	1,279E-07	0	3,95E-06	7,72031E-07	2,04769E-07	3,8E-08
RR, wood	1,10527E-07	4,62E-08	6,12E-08	4,77E-08	1,1702E-13	3,06049E-09	0	2,42E-07	2,14809E-08	7,80631E-08	9,39E-10

Table 85: Recourses for solar cells per function unit for 30 years lifetime.

	Sand	MG silicon	SoG silicon(siemens)	silicon prod. mix	CZ mono-Si	Wafer sawing	cell production	Metallization paste front	Metallization paste back contact	Metallization paste back, alluminium
NRR, aluminium	6,1627E-10	1,85244E-07	5,34757E-07	0	1,2321E-06	1,90788E-06	1,3312E-05	1,3539E-07	6,9357E-08	1,2176E-05
NRR, antimony	3,5785E-18	6,77453E-16	4,15522E-15	0	2,3339E-14	2,59823E-11	1,57012E-12	4,7704E-16	2,4454E-16	2,0096E-16
NRR, brown coal	5,2094E-08	1,24355E-05	0,00010901	0	0,00311811	0,000933078	0,001430911	2,2228E-05	1,1393E-05	1,3457E-05
NRR, cadmium	3,4309E-13	3,2838E-11	2,31922E-10	0	2,2904E-10	3,25624E-10	1,84241E-10	2,9924E-11	1,5331E-11	6,4086E-12
NRR, coal	5,9159E-08	0,00030159	0,00012453	0	0,0017633	0,000764016	0,000859158	8,4085E-06	4,3258E-06	2,1731E-05
NRR, cobalt	2,8285E-14	1,91585E-13	1,0596E-12	2,95139E-14	1,1199E-12	2,20716E-12	1,35429E-12	2,3807E-13	1,2188E-13	1,3918E-13
NRR, copper	3,3796E-10	1,11892E-07	4,90403E-07	3,9208E-09	1,1518E-06	1,84173E-06	1,24746E-06	2,7215E-07	1,3928E-07	6,8871E-08
NRR, gold	1,0463E-15	6,07397E-13	2,64271E-11	0	9,2606E-12	2,38035E-11	1,32354E-11	3,6816E-13	1,9307E-13	1,9776E-13
NRR, iron	3,0845E-08	3,60596E-06	2,7181E-05	1,64386E-06	2,7742E-05	0,00025319	5,00531E-05	1,4976E-06	7,6787E-07	6,2565E-07
NRR, lead	1,322E-11	8,00481E-09	1,48899E-08	5,03588E-11	1,7709E-07	1,31473E-07	8,76963E-08	1,9527E-08	1,9041E-08	3,2759E-09
NRR, manganese	2,7016E-10	1,43222E-08	1,10281E-07	-8,28043E-09	7,8601E-08	3,80096E-06	3,94418E-07	3,3557E-09	1,7244E-09	1,4244E-09
NRR, mercury	1,4325E-15	7,73626E-13	3,96304E-10	0	4,7265E-11	2,88574E-10	1,42264E-10	1,1313E-12	6,0473E-13	2,6705E-12
NRR, molybdenum	1,3862E-11	2,12099E-09	1,08606E-08	0	1,9761E-08	1,51825E-07	6,8524E-08	2,8282E-08	1,4467E-08	1,0699E-09
NRR, natural gas	6,992E-08	1,41602E-05	0,001900665	0,000364023	0,00112894	0,000546394	0,000523912	6,6794E-06	3,4952E-06	6,3736E-06
NRR, nickel	1,1811E-09	1,85021E-07	1,30897E-06	0	1,284E-06	1,56397E-05	2,76434E-06	2,1522E-07	1,1021E-07	1,9588E-08
NRR, oil	1,0749E-06	0,000124664	8,2441E-05	0	0,00030348	0,000446107	0,000212442	1,4827E-05	7,6764E-06	1,4194E-05
NRR, palladium	3,5847E-15	5,37719E-13	1,28816E-12	0	1,5744E-12	2,08468E-12	1,28991E-12	6,9869E-14	3,5962E-14	5,4638E-14
NRR, platinum	1,3208E-16	4,04625E-14	8,22844E-13	1,6604E-13	7,0619E-13	2,96128E-13	3,61864E-13	3,3441E-15	1,7168E-15	2,1521E-15
NRR, silver	3,2017E-15	1,66679E-12	7,09709E-11	0	3,7167E-11	6,7247E-11	1,34827E-06	8,7565E-07	4,4785E-07	5,4149E-13
NRR, tantalum	1,1328E-15	6,01788E-13	2,57348E-11	0	1,2593E-11	2,41201E-11	1,44422E-11	3,6146E-13	1,8952E-13	1,9558E-13
NRR, tin	4,638E-12	6,62852E-11	1,82311E-09	8,88474E-11	4,2539E-09	1,72227E-09	1,09495E-09	4,705E-11	2,4281E-11	1,5151E-11
NRR, zinc	5,549E-10	2,63745E-08	1,44649E-07	0	3,6417E-07	1,11628E-06	1,7318E-07	1,4294E-08	7,3354E-09	1,739E-09
RR, wood	8,3731E-12	4,14157E-07	6,63298E-08	0	2,6082E-07	2,36543E-07	1,45249E-07	1,9185E-09	9,8395E-10	7,9866E-10

Table 86: Recourses for PV system per function unit for 40 years lifetime.

	Sand	MG silicon	SoG silicon(siemens)	silicon prod. mix	CZ mono-Si	Wafer sawing	cell production	Metallization paste front	Metallization paste back contact	Metallization paste back, alluminium
non-renewable resources, aluminium	8,0194E-10	2,41055E-07	6,95871E-07	0	1,6033E-06	2,4827E-06	1,73227E-05	1,7618E-07	9,0254E-08	1,5845E-05
non-renewable resources, antimony	4,6567E-18	8,81559E-16	5,40712E-15	0	3,0371E-14	3,38104E-11	2,04317E-12	6,2076E-16	3,1822E-16	2,615E-16
non-renewable resources, brown coal	6,779E-08	1,61821E-05	0,000141853	0	0,00405755	0,001214199	0,001862022	2,8925E-05	1,4826E-05	1,7512E-05
non-renewable resources, cadmium	4,4645E-13	4,27316E-11	3,01797E-10	0	2,9805E-10	4,23729E-10	2,39751E-10	3,8939E-11	1,995E-11	8,3394E-12
non-renewable resources, coal	7,6983E-08	0,000392455	0,000162049	0	0,00229455	0,000994202	0,001118009	1,0942E-05	5,6291E-06	2,8278E-05
non-renewable resources, cobalt	3,6807E-14	2,49306E-13	1,37885E-12	3,8406E-14	1,4573E-12	2,87214E-12	1,76232E-12	3,0979E-13	1,586E-13	1,8111E-13
non-renewable resources, copper	4,3978E-10	1,45603E-07	6,38154E-07	5,10207E-09	1,4989E-06	2,39662E-06	1,6233E-06	3,5415E-07	1,8125E-07	8,9621E-08
non-renewable resources, gold	1,3615E-15	7,90396E-13	3,43891E-11	0	1,2051E-11	3,09752E-11	1,7223E-11	4,7908E-13	2,5124E-13	2,5735E-13
non-renewable resources, iron	4,0138E-08	4,69238E-06	3,53702E-05	2,13913E-06	3,6101E-05	0,000329472	6,51333E-05	1,9488E-06	9,9922E-07	8,1415E-07
non-renewable resources, lead	1,7203E-11	1,04165E-08	1,93759E-08	6,55312E-11	2,3045E-07	1,71083E-07	1,14118E-07	2,5411E-08	2,4778E-08	4,2629E-09
non-renewable resources, manganese	3,5155E-10	1,86373E-08	1,43507E-07	-1,07752E-08	1,0228E-07	4,94613E-06	5,1325E-07	4,3667E-09	2,2439E-09	1,8535E-09
non-renewable resources, mercury	1,8641E-15	1,00671E-12	5,15705E-10	0	6,1506E-11	3,75517E-10	1,85126E-10	1,4722E-12	7,8692E-13	3,4751E-12
non-renewable resources, molybdenum	1,8039E-11	2,76002E-09	1,41327E-08	0	2,5715E-08	1,97567E-07	8,91692E-08	3,6804E-08	1,8826E-08	1,3922E-09
non-renewable resources, natural gas	9,0985E-08	1,84265E-05	0,002473306	0,000473697	0,00146907	0,000711013	0,000681758	8,6918E-06	4,5482E-06	8,2938E-06
non-renewable resources, nickel	1,5369E-09	2,40765E-07	1,70334E-06	0	1,6709E-06	2,03516E-05	3,59719E-06	2,8006E-07	1,4341E-07	2,5489E-08
non-renewable resources, oil	1,3988E-06	0,000162223	0,000107279	0	0,00039492	0,000580513	0,000276448	1,9294E-05	9,9891E-06	1,8471E-05
non-renewable resources, palladium	4,6647E-15	6,99725E-13	1,67626E-12	0	2,0487E-12	2,71276E-12	1,67853E-12	9,0919E-14	4,6797E-14	7,11E-14
non-renewable resources, platinum	1,7187E-16	5,26533E-14	1,07075E-12	2,16066E-13	9,1896E-13	3,85347E-13	4,70888E-13	4,3517E-15	2,2341E-15	2,8005E-15
non-renewable resources, silver	4,1664E-15	2,16896E-12	9,23533E-11	0	4,8364E-11	8,75075E-11	1,75449E-06	1,1395E-06	5,8278E-07	7,0464E-13
non-renewable resources, tantalum	1,4741E-15	7,83098E-13	3,34882E-11	0	1,6387E-11	3,13871E-11	1,87934E-11	4,7036E-13	2,4662E-13	2,545E-13
non-renewable resources, tin	6,0354E-12	8,62559E-11	2,37238E-09	1,15616E-10	5,5355E-09	2,24117E-09	1,42484E-09	6,1225E-11	3,1597E-11	1,9716E-11
non-renewable resources, zinc	7,2208E-10	3,43207E-08	1,88229E-07	0	4,7389E-07	1,45259E-06	2,25357E-07	1,8601E-08	9,5455E-09	2,263E-09
renewable resources, wood	1,0896E-11	5,38936E-07	8,63139E-08	0	3,394E-07	3,07809E-07	1,89011E-07	2,4965E-09	1,2804E-09	1,0393E-09

Table 87: Energy production during 30 and 4o years for optimal tilted 3 000 Wp PV system in Denmark including degradation.

	Specific annual yield	925	kWh/kWp		
	Degradation	0,50%			
Year	Power kWp	Production (kWh per year)			
1	3,00	2775,00			
2	2,99	2761,13			
3	2,97	2747,32			
4	2,96	2733,58			
5	2,94	2719,91			
6	2,93	2706,32			
7	2,91	2692,78			
8	2,90	2679,32			
9	2,88	2665,92			
10	2,87	2652,59			
11	2,85	2639,33			
12	2,84	2626,13			
13	2,82	2613,00			
14	2,81	2599,94			
15	2,80	2586,94			
16	2,78	2574,00			
17	2,77	2561,13			
18	2,75	2548,33			
19	2,74	2535,59			
20	2,73	2522,91			
21	2,71	2510,29			
22	2,70	2497,74			
23	2,69	2485,25			
24	2,67	2472,83			
25	2,66	2460,46			
26	2,65	2448,16			
27	2,63	2435,92			
28	2,62	2423,74			
29	2,61	2411,62			
30	2,59	2399,56	30 years	77486,77	kWh
31	2,58	2387,57			
32	2,57	2375,63			
33	2,56	2363,75			
34	2,54	2351,93			
35	2,53	2340,17			
36	2,52	2328,47			
37	2,50	2316,83			
38	2,49	2305,24			
39	2,48	2293,72			
40	2,47	2282,25	40 years	100832,33	kWh

Table 88: Raw data for the comparison between 270 and 180 micrometer thick solar cells.

270 micrometer	Panel							BOS			
	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport		Inverter	Electric installation	roof installation	Transport
Global Warming Potential, 100 years	0,0431101	0,00063854	0,000243277	0,00041068	3,186E-06	0,000619008		0,004756812	0,001644441	0,00681147	0,0002491
Acidification Potential	0,0001573	2,0443E-06	8,43359E-07	2,1208E-06	1,067E-08	2,60905E-06		4,35532E-05	2,43148E-05	2,7608E-05	7,383E-07
Eutrophication Potential	9,817E-05	1,2925E-06	1,37088E-06	8,3489E-07	6,371E-09	3,06989E-06		1,96588E-05	7,69357E-06	1,7605E-05	1,01E-06
Ozon Depletion Potential, 10 years	1,927E-08	3,8137E-11	2,97072E-11	5,6409E-11	1,094E-15	8,4924E-11		5,28684E-10	4,99717E-11	5,3944E-10	3,502E-11
Human Toxicity Potential, 100 years	0,0141225	0,00013491	0,000620922	8,7536E-05	1,677E-08	0,000112399		0,01874178	0,013952376	0,04082123	3,633E-05
Ionizing Radiation Potential	2,025E-11	3,0563E-12	8,80501E-12	9,5593E-13	4,561E-17	1,31033E-12		4,60956E-11	6,55354E-12	6,109E-11	6,004E-13
Water	0,0008652	0,00607113	0,047197191	0,00851886	5,634E-06	0,002564344		0,060144461	0,01235107	0,05374349	0,0009812
Land	0,001157	4,861E-05	0,000198277	6,3251E-05	3,557E-10	1,01498E-05		0,000403837	4,55181E-05	0,00036616	5,161E-06
Resources	0,0203429	0,00049807	0,000795053	0,00018964	2,61E-06	0,000332098		0,003003423	0,000786311	0,00249345	0,0001014
Cumulative Energy Demand	0,2240758	0,00603001	0,000908761	0,00192716	3,511E-05	0,004520211		0,024531979	0,007667906	0,03691865	0,0010806
Renewable Energy	0,0335995	0,00017516	2,45063E-05	0,00019878	4,083E-07	6,68527E-05		0,001796166	0,000388049	0,00567476	1,654E-05
Non-Renewable Energy	0,1904646	0,00585484	0,000884254	0,00172838	3,47E-05	0,004453358		0,022735813	0,007279858	0,03124389	0,0010641

180 micrometer	Panel							BOS			
	Solar cells	Encapsulate	Front and back glass	AR-coating	Protective back sheet	Transport		Inverter	Electric installation	roof installation	Transport
Global Warming Potential, 100 years	0,0334882	0,00063854	0,000243277	0,00041068	3,186E-06	0,000619008	0	0,004756812	0,001644441	0,00681147	0,0002491
Acidification Potential	0,0001266	2,0443E-06	8,43359E-07	2,1208E-06	1,067E-08	2,60905E-06	0	4,35532E-05	2,43148E-05	2,7608E-05	7,383E-07
Eutrophication Potential	7,726E-05	1,2925E-06	1,37088E-06	8,3489E-07	6,371E-09	3,06989E-06	0	1,96588E-05	7,69357E-06	1,7605E-05	1,01E-06
Ozon Depletion Potential, 10 years	1,844E-08	3,8137E-11	2,97072E-11	5,6409E-11	1,094E-15	8,4924E-11	0	5,28684E-10	4,99717E-11	5,3944E-10	3,502E-11
Human Toxicity Potential, 100 years	0,013073	0,00013491	0,000620922	8,7536E-05	1,677E-08	0,000112399	0	0,01874178	0,013952376	0,04082123	3,633E-05
Ionizing Radiation Potential	1,66E-11	3,0563E-12	8,80501E-12	9,5593E-13	4,561E-17	1,31033E-12	0	4,60956E-11	6,55354E-12	6,109E-11	6,004E-13
Water	0,0006543	0,00607113	0,047197191	0,00851886	5,634E-06	0,002564344	0	0,060144461	0,01235107	0,05374349	0,0009812
Land	0,000945	4,861E-05	0,000198277	6,3251E-05	3,557E-10	1,01498E-05	0	0,000403837	4,55181E-05	0,00036616	5,161E-06
Resources	0,0081669	0,00049807	0,000795053	0,00018964	2,61E-06	0,000332098	0	0,003003423	0,000786311	0,00249345	0,0001014
Cumulative Energy Demand	0,1740152	0,00603001	0,000908761	0,00192716	3,511E-05	0,004520211	0	0,024531979	0,007667906	0,03691865	0,0010806
Renewable Energy	0,0245736	0,00017516	2,45063E-05	0,00019878	4,083E-07	6,68527E-05	0	0,001796166	0,000388049	0,00567476	1,654E-05
Non-Renewable Energy	0,1494303	0,00585484	0,000884254	0,00172838	3,47E-05	0,004453358	0	0,022735813	0,007279858	0,03124389	0,0010641