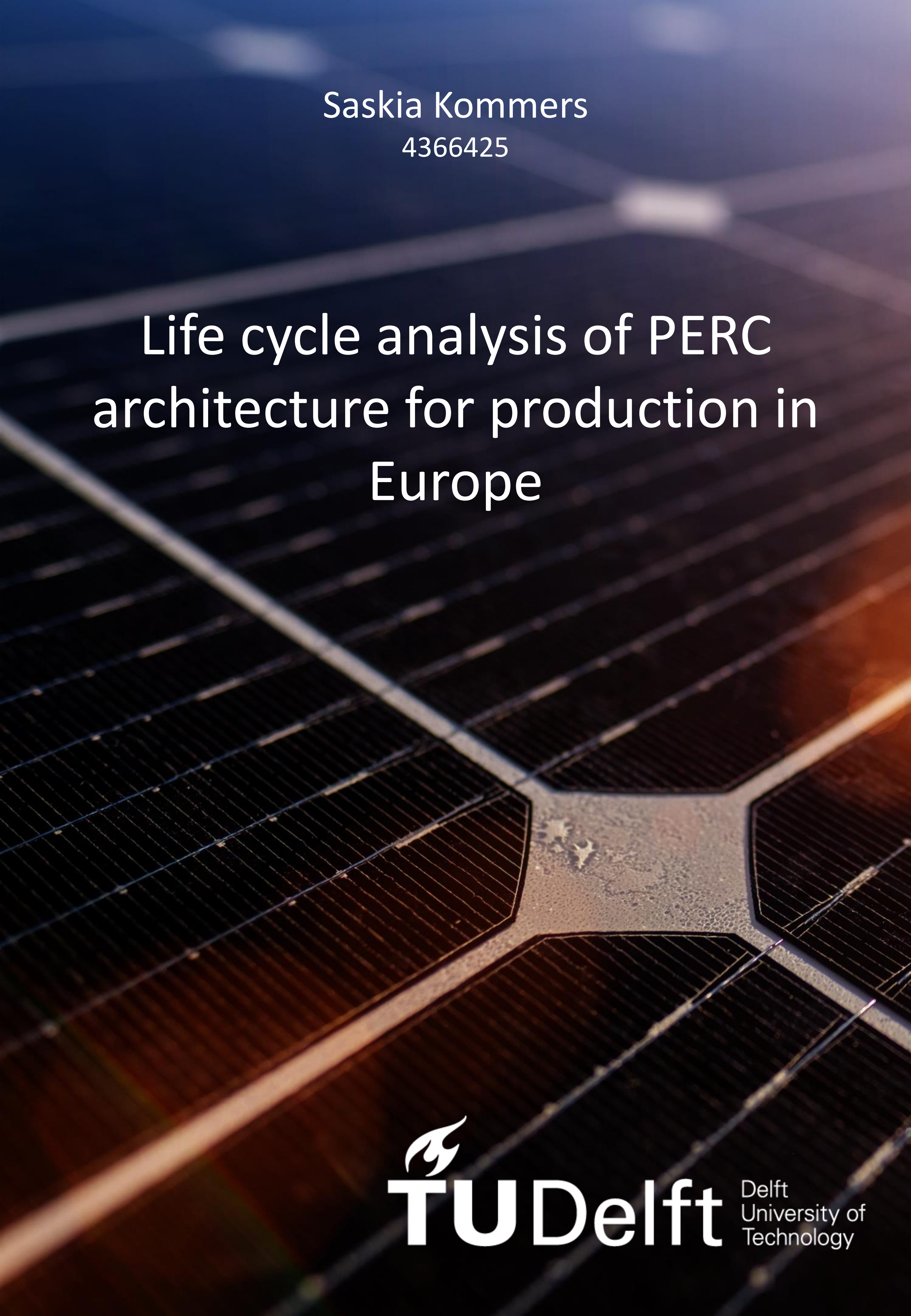

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Life cycle analysis of PERC architecture for production in Europe

TU Delft
Delft University of Technology

Life cycle analysis of PERC architecture for production in Europe

Thesis report

by

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to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on August 30, 2023 at 15:00

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An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Delft University of Technology

Abstract

The worldwide energy need is increasing and the share of renewable energy sources is too. To generate electricity from renewable sources, no harm to the environment is done. But producing a PV panel is not without emissions. The amount of emissions during production is researched with a life cycle analysis.

In the current PV market 75% of the installed capacity is Passivated Emitter and Rear Cell (PERC), so this is the cell type that will be analysed. The majority of PV panels are produced in China, but for this study Europe is chosen as the location of production. When panels are produced in Europe the electricity mix of Europe is used, which consists of less fossil fuels and more renewable sources. Production in Europe also

Previous LCA studies on solar panels are performed on PERC panels but in Asia, or on Al-BSF panels in Europe. One study is found on a PERC panel produced in Europe, and its inventory is used for this study.

The goal of this study is to calculate the impact of producing a PERC PV panel and compare it to other studies on PV panels and to other energy sources. The functional unit is 1 kWh, and the system boundary includes the phases cradle-to-gate.

Two inventories are used, one for Al-BSF produced in 2018 and one for PERC produced in 2021. The PERC inventory is then altered to represent a panel produced in 2022, 2023, and 2030. The assessment of the panels is done using IDEMAT and Ecoinvent 3.8.

The results for the PERC panel produced in 2022 are: climate change 1.09E-02 kcCO_2/kWh, ozone depletion 1.09E-08 kg CFC11/kWh, ionising radiation 2.50E-05 kBq U-235/kWh, photochemical ozone formation 4.12E-05 kg NMVOC/kWh, particulate matter 2.69 disease/kWh, non-cancer human health 7.37E-11 CTUh/kWh, cancer human health 2.35E-11 CTUh/kWh, acidification 4.40E-05 mol H^+/kWh, freshwater eutrophication 5.39E-07 kg P/kWh, marine eutrophication 5.12E-06 kg N/kWh, terrestrial eutrophication 5.50E-05 mol N/kWh, ecotoxicity 1.06E-02 CTUe/kWh, land use 1.24E-03 pt/kWh, water use 5.25E-05 m^3/kWh, resource use fossil 1.59E-01 MJ/kWh, resource use mineral & metals 1.29E-06.

In terms of climate change a PV panel has lower missions than wind power and the Europe electricity mix, but higher emissions than nuclear power and hydro power. PV has lower particulate matter emissions than nuclear, wind power, and the Europe electricity mix, and higher than hydro power. For non cancer human health, PV is lower than nuclear and wind power, but higher than hydropower and Europe electricity mix. PV power has a lower amount of acidification than wind power, nuclear power and the Europe electricity mix, but higher than hydro power. For ecotoxicity PV has a lower value than wind power and nuclear power, but higher than hydro power and the Europe electricity mix.

Acknowledgements

In this chapter I would like to take a moment to thank the people around me who helped me during my research. First I would like to thank my supervisor Malte Vogt for his guidance and support throughout this project. I would also like to thank Chengjian Xu for sharing is broad knowledge and taking the time to explain the ins and outs of LCA.

Furthermore I would like to thank my family for their unconditional support, not only for this thesis but during my whole studies. For my friends i show the same gratitude for their support.

Lastly, I would like to thank Maarten for proofreading this report and the overall support and encouragement during my masters.

Saskia Kommers
Delft, 2023

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List of abbreviations

Al-BSF aluminum back surface field. ii, vii, 1, 4, 5, 19, 20, 26–30, 32–34, 36–40, 44, 45

ARC Anti Reflective Coating. 16

BoS Balance of System. 5

c-Si crystalline silicon. 3–5

CTUh Comparative Toxic Unit for humans. 23

GHG Greenhouse Gas. 1, 3, 22

GWP Global Warming Potential. 22

IAE International Energy Agency. 4, 5

IDEMAT Industrial Design & Engineering MATerials database. ii, 19–22, 24, 27, 29, 30, 37, 38, 41

LCA Life Cycle Analysis. 2, 7–10, 17, 19, 22, 24, 41, 44

LCI life cycle inventory. 7, 9, 11

LCIA life cycle impact assessment. 7, 8, 10, 11, 26

LCO Laser Contact Opening. 16

NMVOC non-methane volatile organic compounds. 23

ODP Ozone Depletion Potential. 22

PECVD plasma enhanced chemical vapour deposition. 16

PERC Passivated Emitter and Rear Cell. ii, vii, 1, 5, 6, 12, 14, 17, 19, 20, 26–30, 32–41, 44, 45

PM particulate matter. 23

PV photovoltaic. ii, vi, vii, 1, 3–6, 12, 16, 17, 19, 20, 26, 27, 32, 35, 37, 38, 41, 43–45

PVPS Photovoltaic Power Systems Programme. 4, 5, 19

Chapter 1

Introduction

The worldwide primary energy need is constantly increasing. In the last decade, the global energy consumption has grown by 20% [1]. The COVID-19 pandemic has led to a reduction in energy demand of 2% in 2020. However, this decrease has been overhauled by a subsequent growth in energy demand in 2021 [2]. This growth is expected to last until 2030, after which it is forecasted to plateau, due to increasing energy efficiency and behavioural change [3].

Around 80% of today's energy supply stems from fossil fuels, and the energy sector itself is responsible for almost 75% of global Greenhouse Gas (GHG) emissions [3]. These gasses form a significant causal agent for global warming and climate change in general [4]. These negative developments have been summarised during the 2015 Paris Agreement, leading to an accord to limit the global temperature rise to 2°C, and pursuing efforts to limit it to 1.5°C [5]. To reach this goal, the amount of GHG emitted should be lowered drastically. An effective way of achieving this would be the gradual but swift substitution of oil, gas and coal, with renewable alternatives such as wind power, solar power and hydropower.

Renewable energy sources are on the rise, as seen in Figure 1.1. Solar and wind power are low in costs, can be installed worldwide and are supported with policies in over 130 countries. Their capacity has grown tremendously, and will triple over the next decade. The share of solar and wind power of the total electricity generation rises from under 10% in 2020 to nearly 30% in 2030 [3].

Solar power is seen as one of the environmentally friendly way of creating electricity. However, the production process of photovoltaic (PV) panels is not without emissions. Material extraction, production, transport or decommissioning and recycling are all steps in the production process of PV panels where GHG's are emitted. The goal of this study is to research the environmental impact and analyse the life cycle of PV panels.

1.1 Cell types

The PV market consists of a wide range of different solar cells. This thesis will focus on the Passivated Emitter and Rear Cell (PERC), the most prevalent solar cell used in the current PV market. Previously, the most produced solar cell was aluminum back surface field (Al-BSF). These cells have been the standard since PV's inception and are still being produced to this day. The highest efficiency in mass-produced Al-BSF cells is 20% [7].

The efficiency of mass produced PERC cells are higher than Al-BSF cells. The highest efficiency is now at 24.5%, produced by Trina Solar [8]. Due to the higher efficiency, the PERC has gained popularity and had a rising share in PV cell production. Market shares of PERC have caught up with BSF cells in 2019 and keep out-performing them in the next

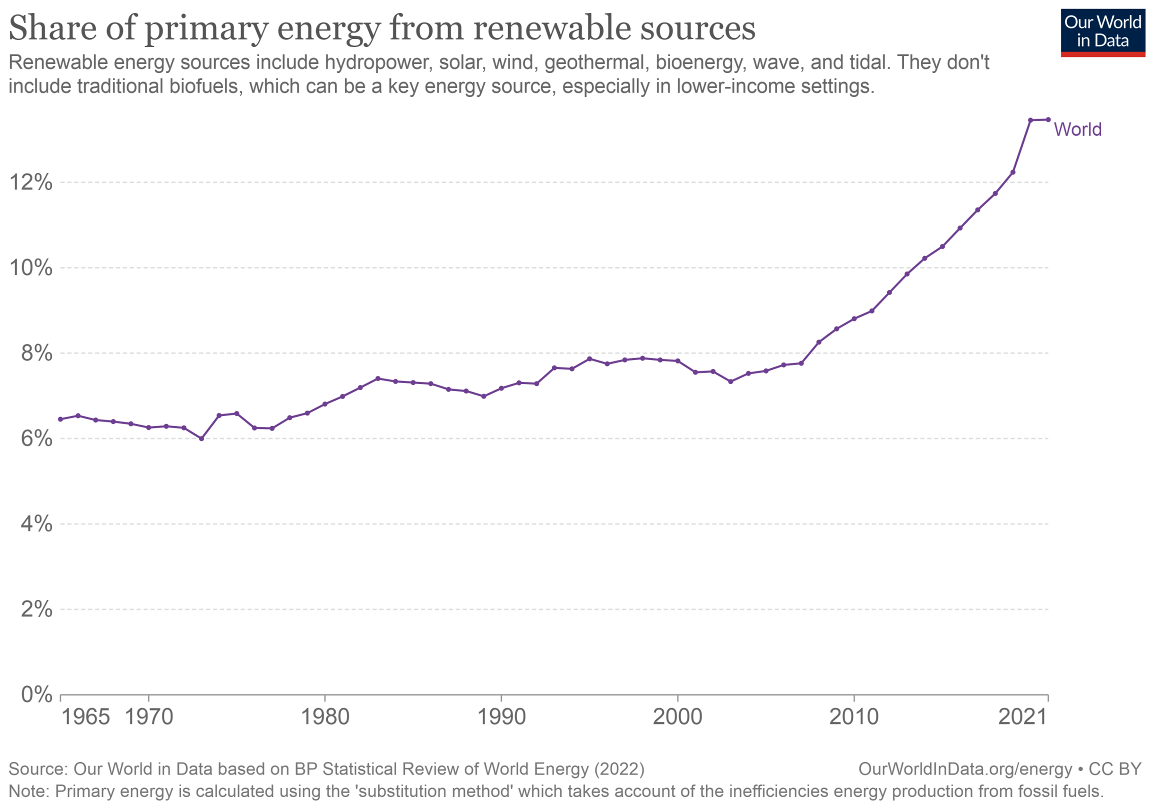


Figure 1.1: Share of primary energy from renewable sources [6]

few years, as shown in Figure 1.2 [9]. Currently, 75% of total installed capacity of PV panels worldwide use PERC [10]. Furthermore, given their large share in the PV market, they prove to be the appropriate choice of cell type to use for this LCA.

1.2 Life Cycle Analysis

Measuring the environmental impact of a product like PV panels can be done by performing a Life Cycle Analysis (LCA). LCA is a method used to quantify material and energy flows, and that measures the impact of the complete life cycle of the product. The total life cycle of a product can affect the environment in many ways. The impact of producing, using, and decommissioning a product can cause damage to ecosystems, human health, and other animal life.

An LCA can be performed for different purposes such as creating a novel product with low environmental impact. Another use of LCA is to optimise an existing product by minimising the use of materials and use of energy during production, or by a different material selection. The results can help in the development of products to see what part of the process has the biggest impact. This knowledge can be used to influence design choices, to render a more sustainable product which will reduce the gap to set carbon footprint goals. Another option of LCA is to calculate the environmental burden of a project for marketing purposes and to attract investors. An LCA can also be used to compare products and select the product with the lowest environmental impact. An LCA can help in the decision making in industry or government.

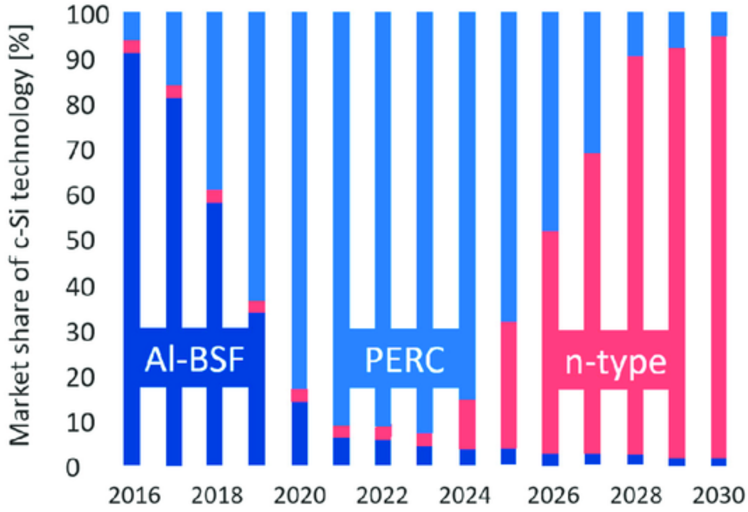


Figure 1.2: Current and projected global market shares of c-Si cell concepts [11]

1.3 Location

Currently, the majority of solar cells are produced in China. In 2021, 93% of the total crystalline silicon (c-Si) PV modules were made in Asia. China alone produced 70% of the total amount of c-Si PV modules. In comparison, Europe produced only 3% [12]. Figure 1.3 shows the growth of production per location, where the growth of PV production in Asia can be seen. For increasing the production of PV cells in Europe, the following arguments can be made.

Firstly, 84% of the total primary energy consumption in China stems from fossil fuels. Conversely, the use of fossil fuels in Europe amounts to 70% of total energy consumption [13]. For the same amount of energy needed to produce a PV panel, less Greenhouse Gasses are emitted in Europe. Moreover, solar panels produced in Europe require substantially less transport to the European market. These two factors combined, make for a lower environmental impact for the production of an identical PV panel.

Secondly, since 70% of production stems from one country, the governmental regulations from said country can have a high impact on PV panel supply worldwide. Since the importance of PV to transition to a more sustainable energy supply, it can be argued that the production of PV should be more equally divided per country to minimise the risk of governmental influence and secure the transition.

Many of the production facilities in China make use of European production machines. This means that there is no confidentiality, and European facilities are able to use the same machines. With all relevant technological knowledge residing in Europe and a lot of research and development currently being carried out in Europe, there is little to no technological boundary to increase production in Europe. The supply of raw materials is also not an issue, since all materials are available in Europe. Furthermore, the increase of automation during the production process will lead to a reduction in employment, ensuing that labor forces are becoming less of a contributing factor [14].

Together, these arguments suggest that an increase of PV production in Europe can have a positive effect on the PV market. Therefore, this LCA focuses on solar panels that are created in Europe.

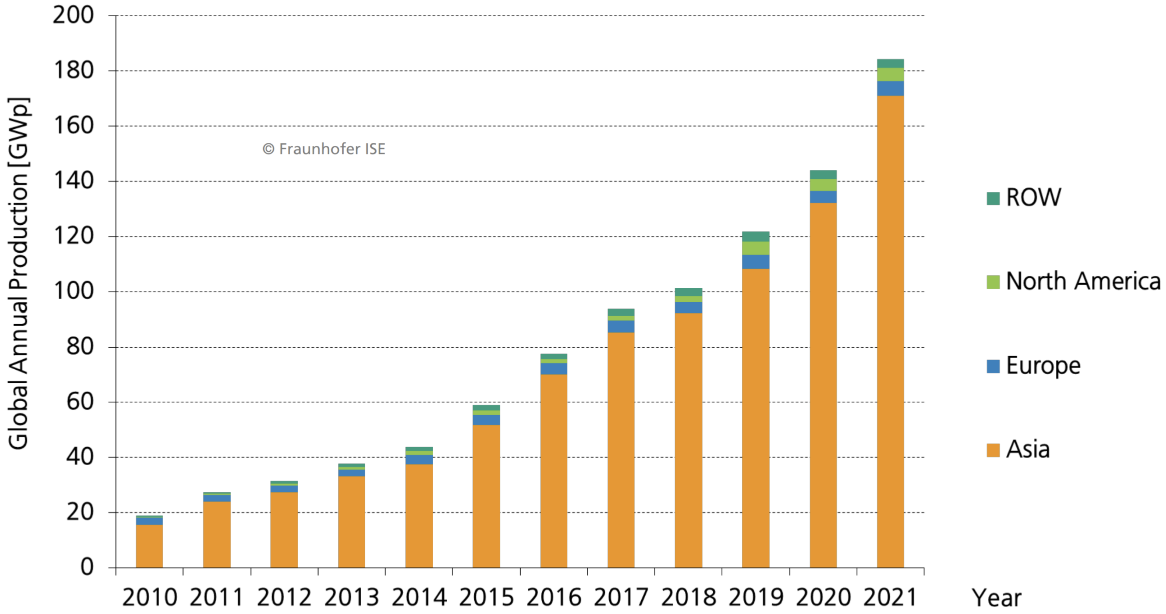


Figure 1.3: Global annual production of PV panels per location [12]

1.4 Previous LCA's

The combination of the cell type and location make for a unique LCA. Previous reports of LCA's of PERC cells exist, albeit under different circumstances. Most LCA's have been performed on solar cells produced in China [15], [16]. This means different circumstances and energy source mix, which influences the results. Nevertheless, data from these studies can be used to compare to the LCA of this thesis to show the influence of energy source mix.

With the fast growing world of PV, and its technology improving at a high rate, reports are quickly outdated. With the fast improvements of PV technology, only the current reports can be used for research. Older LCA reports are done on older PV modules with lower efficiencies [17]. Efficiencies have improved, and production circumstances have changed. For every study, the most current technology has to be used. An LCA done on older PV panels can still be useful for comparison to show how much the panels or technology have improved over time.

Some other LCA's performed on production in Europe are carried out on different type of cells [18]. This is still useful, as comparison to this LCA. If both LCAs are conducted with current data, it shows what type of cell has lower impact, since the place of production is identical.

In the results section, this study will be compared to other LCA studies. The studies are summarised in Table 1.1. The first study is from Photovoltaic Power Systems Programme (PVPS), by International Energy Agency (IAE) [19]. This study from 2020 reflects on the production of PV panels in 2018. This is an update on the same study performed in 2015, which reflects production in 2011. In this study, several cell types are calculated, namely monocrystalline silicone (mono-c-Si), multicrystalline silicon (multi-c-Si), thin-film CdTe, thin-film CIGS, and thin-film perovskite silicon tandem. The mono-c-Si panels are Al-BSF. The study focusses on PV panels produced in China, Europe, Asia & Pacific, and Americas. This study does not contain results on impact, but PVPS released a seperate datasheet with data on environmental impacts. This datasheet uses the complete life cycle, from raw materials until end-of-life. The functional unit is 1 kWh and the lifetime is 30 years. The inventory of the study is used in this thesis to make calculations of the mono-c-Si cell with production in Europe and is used for comparison to the datasheet and other studies.

The next LCA study used for comparison, is the LCA study performed by A. Müller [20]. This study uses the inventory form Fraunhofer ISE. This database is based on PERC specific modules, with production located in Europe. The emissions are based on Ecoinvent. A p-type PERC cell with a M6 (166mm) size is calculated, from cradle-to-grave, excluding BoS and maintenance. The definition of 'cradle-to-grave' and other variations will be discussed in Chapter 2. The functional units are 1 kWp and 1 kWh. For the calculation per 1 kWp the standard test conditions are used, while the calculations per 1 kWh include the performance of the solar panel under different circumstances, such as the varying solar irradiance and performance loss of the panel. The entire life cycle is used, excluding the BoS and use phase. The inventory from this study will be used as the base for this thesis. From here, alterations will be made to make the study up to date.

The third results are from the Ecoinvent 3.7 database. In this database, a c-Si PV module is used, produced in the year 2005. Due to the rapid innovation of PV, this study can be classified as outdated. However, it is still useful for comparison, to show how much innovation has made a difference in the impact on the environment in the last two decades. The results of the inventory are calculated using the software SimaPro, and listed in the study of Müller. The functional unit is 1 kWp, and the system boundary of Müller is used.

The fourth study is from PVPS, by IAE [17]. For this result, the inventory from the first version is used, published in 2015. This study includes a mono-c-Si cell produced in Europe in 2011. The results of the impact calculations are calculated using the software SimaPro, and listed in the study of Müller. The functional unit is 1kWp, and the system boundary of Müller is used.

The fifth study is X. Jia [15]. This study uses a monofacial PERC cell with a wafer size of G1 (158.75 mm). The inventory is made through questionnaires, completed by manufacturers in China. The inventory includes production, installation, use, and End-of-life. The functional unit is 1 kWh of AC. For this type of PV panel, a lifetime of 25 years is assumed. The results are calculated using the SimaPro software.

The sixth is M. Lunardi [16]. The inventory is based on an Al-BSF cell with data from the PVPS report [17], with adaptions from M. Wild-scholten and V. Fthenakis. This is then altered to a p-type monocrystalline PERC cell by differentiating the production steps and the use of information from equipment manufacturers. The whole life cycle is taken into account, from raw materials until the End-of-life. The BoS and recycling is not included. The functional unit for this study if 1 kWh of direct current. The results are calculated using the GaBi software.

The seventh study used for comparison is W. Luo [21]. This study considers a roof-integrated p-type multi-Si PERC cells, with electricity generation in Singapore. The life cycle starts at raw material, and ends at installation of the PV system. The inventory is formed by Solar Energy Research Institute of Singapore at the National University of Singapore. The size of the PERC cell is M0 (156 mm). The calculations are performed for a 25 year lifetime, and with a functional unit of 1 kWh.

Study	Year	Type of cell	Location
PVPS	2020	mono-Si	Europe
Müller	2021	PERC	Europe
Ecoinvent 3.7	2020	c-Si	Europe
PVPS	2015	mono-Si	Europe
Jia	2018	PERC	China
Lunardi	2018	PERC	China
Luo	2018	PERC	Singapore

Table 1.1: List of previous LCA studies on PV modules

1.5 Thesis structure

Chapter 2 describes how the analysis is performed.

In chapter 3, the case study of a PERC cell reported. Section 3.1 explains the production process, to make it understandable what materials are used to make an inventory. Next in section 3.2 the goal and scope are defined. After that the inventory is formed and explained, and assumptions are explained in section 3.3. Section 3,4 explains the methodology.

The results of the assessment are shown in chapter 4. Here the results are compared to other studies, both PV and other energy sources. The conclusion and discussion can be found in chapter 5.

Chapter 2

Life Cycle Analysis principle

For performing a Life Cycle Analysis, the guidelines of ISO14040 are followed [22][23]. According to these guidelines, an LCA consists of four phases: the scope and goal definition phase, the life cycle inventory (LCI) phase, the life cycle impact assessment (LCIA) phase, and the interpretation phase. These are further explained per subsection.

A distinction can be made between a rigorous LCA and a fast track LCA. A rigorous LCA study means first making an inventory of the unit processes inside the boundary system. All the LCI of the subsystems are added to compile one inventory list. The emissions in this list must be assigned to an impact indicator. The LCA practitioner is free to choose which indicator system to use. In this classical approach, specialised software is needed for calculations, like SimaPro, GaBi, or Open LCA. A rigorous LCA is more complex and is more time consuming. A fast track LCA differs most in the LCIA phase. The steps of classification, characterisation, normalisation, grouping, and weighting can be skipped since this is already defined by choosing the indicators in the first step of the LCA.

The complete process of making a product is called the product system. This system consist of separate production steps. A single production step is called a unit process. The reference product at the output of one unit process is used as input for the next unit process. This is depicted in Figure 2.1.

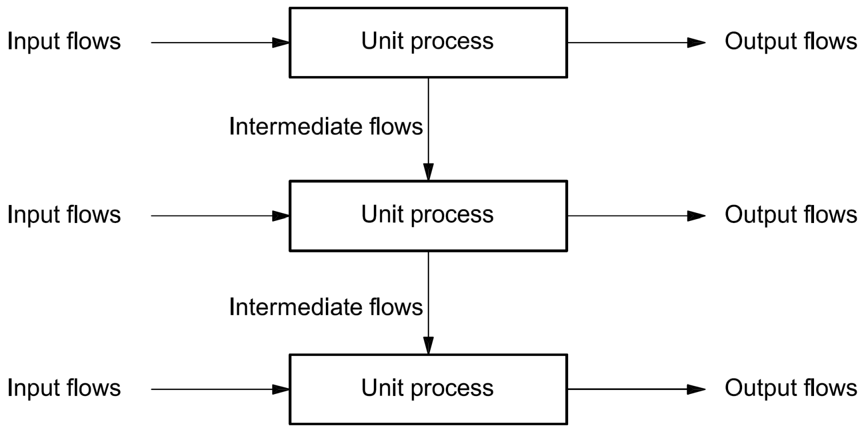


Figure 2.1: Unit processes [24]

2.1 Goal and scope definition phase

An LCA starts by defining the goal and scope. Within the goal, the reason of the study is defined, as well as the application of the LCA study and its intended audience. A reason for performing an LCA could be to compare the product to other products in terms of environmental impact, or to improve the product by calculating each production step and make modifications. The intended audience could be industry, government, or non-government.

Next, the scope of the study is defined. It starts with defining the product system to be studied and the functions it performs. Part of the scope is defining the functional unit. The functional unit is a reference unit against which the performance of a product can be quantified. The inputs and output can be related to the functional unit to provide a reference for the LCA results. This is essential to compare the results to other LCA studies with the same functional unit.

The scope includes the system boundary and the level of detail of the LCA. This depends on the subject and the intended use of the study. The system boundary defines which process steps are included in the calculations of the LCA. This makes it clear what assumptions are made, and to what level the calculations are made.

The life cycle starts at the moment material is acquired, and is processed to be used for production of the product. The product is then transported to the location where it is installed. After the installation, the use phases begins. During the use phase, maintenance has to be carried out. When the product is no longer used, it has to be decommissioned after which it is recycled or discarded. If discarded, it can be subject to waste incineration, or it can end up in a landfill. The use-phase and End-of-Life phase are not constant, but are based on the handling of the user.

If an LCA is calculated over the entire lifespan, it is called a 'cradle-to-grave' model. This type of LCA spans from the moment the raw material is acquired, until the End-of-Life. When the use phase and End-of-Life phase are not included, the LCA is labeled 'cradle-to-gate'. Here, the LCA spans only from material acquisition to the product's departure from the factory. In this type of calculation, only the production is included in the calculation. The maintenance during its lifetime is not included, as well as the End-of-Life. The opposite of cradle-to-gate is gate-to-grave, where only the use-phase and the End-of-Life is taken into account. Since it is based on behaviour, the results have a high uncertainty. Another form is gate-to-gate, where only one step of the production process is calculated. It leaves out the former steps of material acquisition and processes, as well as the following production steps.

A division can be made between foreground and background processes. The calculations done inside the system boundary are part of the foreground process. The materials at the input (upstream) are from background processes. These materials are processed from raw materials and are already calculated by other LCA studies. The output from the foreground process is the product. If the use phase and End-of-Life phase are not included in the system boundary, then this is part of the downstream process. The downstream processes are part of background processes. This is depicted in Figure 2.2.
In the first phase of the LCA, the impact categories and methodology must be chosen. This will be used in the LCIA phase. This will be further explained in section 2.3.

The data requirements is stated in the scope, and has the purpose of defining the properties of the data needed. This is essential to understand the reliability of the results. Together

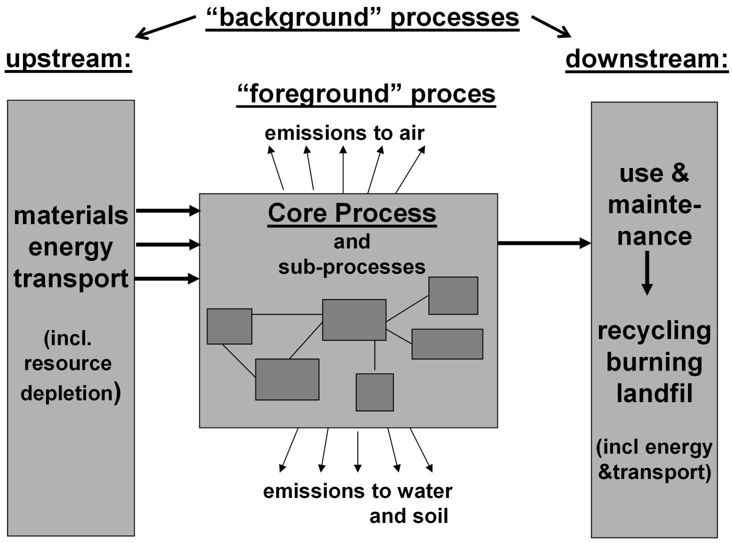


Figure 2.2: foreground and background processes [24]

with the requirements, the assumption and limitations should be stated. Data can be collected or calculated from other sources, obtained from production sites, or can be estimated. The data requirements should specify the geographical area for the unit processes, the specific technology, and the sources of the data.

2.2 Inventory analysis phase

The second phase of an LCA is called the life cycle inventory (LCI) analysis phase. In this phase, an inventory is made of the input and output data. Input data consists of raw materials, processed materials from an upstream process, transport, infrastructure, and energy in the form of heat and electricity. The output data consists of the product or service, by-products, emissions, waste treatment, and energy in the form of heat.

The inventory analysis is done per unit process. All data is collected and an inventory is formed. The collection of the inventory is an iterative process. During an LCA the data requirements can change, or more information about the system is acquired. During the data collection, the data should be validated and be related to the functional unit or reference flow.

In Figure 2.3, the basic calculation model of an LCA is shown. In every step, there is an input of materials and energy, and an output of emissions. The emissions are divided into emissions to air, water, and soil. Between each step, transport is added if needed. If the product is made in one factory, the transport only applies after it leaves the factory and is transported to the consumer. At the last step, the product is recycled, undergoes waste treatment, or ends up in a landfill.
The materials at the start of a system are elementary flows. They describe materials resourced from nature without having been processed by humans. At the output the elementary flow is released back into nature (water, air, soil, or as radiation) without further human interaction.

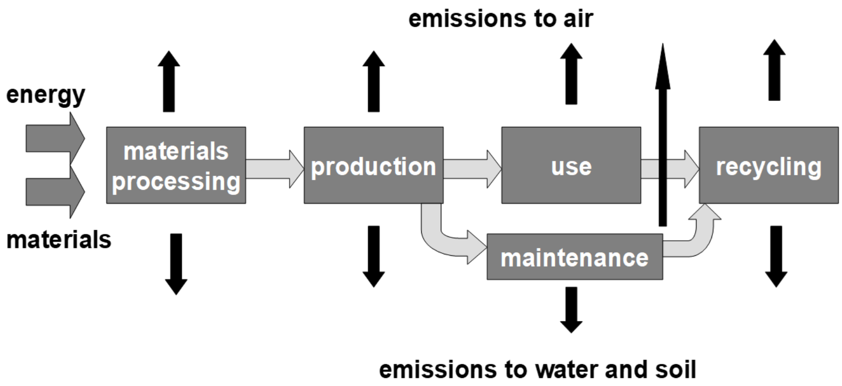


Figure 2.3: LCA calculation model [24]

2.3 Impact assessment phase

The third phase is the life cycle impact assessment (LCIA) phase, and focuses on assessing the inventory made in the previous phase. This assessment helps to gain insight into the significance of the environmental impact the product has.

An LCIA is performed by first choosing the methodology that is going to be used. Each methodology had a different set of impact categories. Each impact category has a category indicator, called the equivalent emission. This differs per category and per methodology. The chosen methodology must fit the goal and scope of the study. The choosing of the methodology, and the goal and scope of the LCA is an iterative process.

Next, the inventory made in the LCA phase is grouped per emission. Each emission is normalised to the equivalent emission. For example, the impact category "Global Warming Potential" uses the equivalent emission carbon dioxide. In the same impact category, the emission methane is listed. 1kg methane is equivalent to 36.8kg carbon dioxide in terms of Global Warming Potential. By using the same units, the list of emissions can be added up to create a total value to quantify the total Global Warming Potential. This process is repeated for every impact category. The values of normalisation are set per methodology.

Optional elements of LCIA are normalization, grouping, and weighting. Normalization relates the category indicator to the literature. It can be used to check for inconsistencies and to show significance. Grouping is the act of sorting the impact categories. This is done on a nominal basis, or on priority. Priority is based on preference and can differ per LCA study. Weighting is grouping together the impact categories.

The impact categories chosen are considered midpoint categories. There are multiple categories all with different impact indicators. To make the results more understandable by non-experts, the categories can be grouped in endpoint categories. The three endpoint categories are natural environment, human health, and resources. Each midpoint category has a relative importance, so a weighting factor is applied to add up the categories to one endpoint category. Since the weighting factor is not a constant, but rather a choice of value, it has no scientific base.

An LCIA can be analysed for quality by three types of analysis. The first one is contribution analysis, where the greatest contributor to a category is identified. This can then be used to further examine this item to ensure the quality of the study, or to identify what production processes can be improved. Next, an uncertainty analysis is used to determine how uncertainties affect the reliability of the results. Finally, a sensitivity analysis determines the how much a change in data, methodology, or calculation can affect the results.

2.4 Interpretation phase

The final phase is the life cycle interpretation phase. In this phase, the results of the LCI or the LCIA, or both are summarised. The results are discussed and a conclusion is formed. This phase is needed to make conclusions, recommendations and is used for decision-making.

Issues or problems of the results of LCI or LCIA are identified, and the study is analysed for completeness and consistency. This ensures that the result of the study is in line with the goal and scope. With all steps completed, the final conclusions can be made. Finally any limitations are stated and recommendations are made.

Chapter 3

PERC PV cell case study

Al-BSF PV panels were the most common used technology, but are being replaced by PERC cell. The difference between the two types is the back surface of the cells, as seen in Figure 3.1. An Al-BSF cell has a full aluminium back surface field, while the PERC cell only has local back surface field. The areas between the local back surface field are covered with a passivation layer. The extra passivation layer reduces the recombination significantly [25], and therefore increases the efficiency of the solar cell.

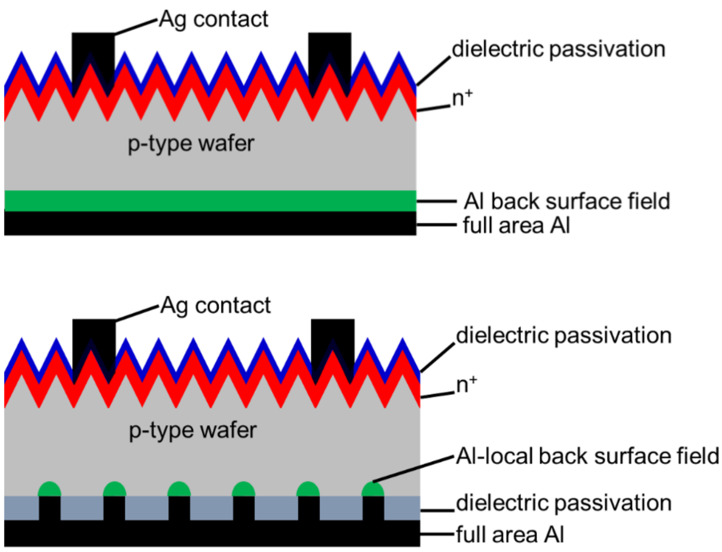


Figure 3.1: Al-BSF (upper) and PERC (lower) [26]

3.1 Production of a PV panel

The first step of production is producing metallurgical grade silicon. This production step starts with silica, also known as silicon dioxide, which is found in quartz sand. Quartz consist about 50% of its mass of silicon. To produce silicon, the oxide must be removed. This is done using carbon, which can come from charcoal, coke, or petroleum coke. Silica and carbon is put in an electric arc furnace, where the following reactions take place.

$$2\,SiO_2(l) + SiC(s) \longrightarrow 3\,SiO(g) + CO(g) \quad (3.1)$$
$$SiO(g) + SiC(s) \longrightarrow 2\,Si(l) + CO(g) \quad (3.2)$$
$$SiO(g) + 2\,C(s) \longrightarrow SiC(s) + CO(g) \quad (3.3)$$
$$2\,SiO(g) \longrightarrow Si(l) + SiO_2(s) \quad (3.4)$$

In the first reaction silicon monoxide and carbon monoxide is formed at the bottom of the furnace at roughly 1900°C. At the same time, silicon oxide and silicon carbide react to form silicon and carbon monoxide. In the upper part of the furnace, the temperature is below 1900°C. Here the third and fourth reaction takes place. The liquid silicon is extracted, cooled and solidified. The extracted silicon is called metallurgical silicon, with a purity of 98% or higher. The exhaust gasses containing silicon are recycled. The process is quite complicated, and involves more than the four equations shown. Figure 3.2 depicts the electric arc furnace, and the reactions taking place within.

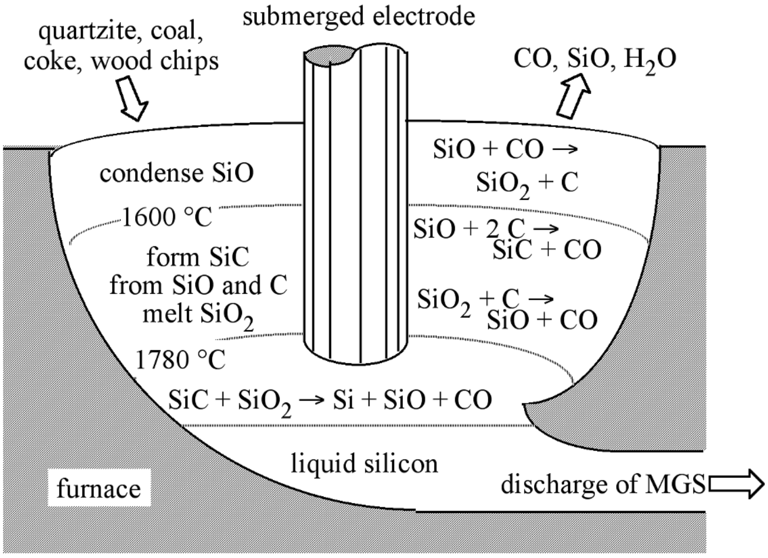


Figure 3.2: Electric arc furnace [27]

The next step of production is the Siemens process [28]. In this process metallurgical silicon is used to produce polysilicon. The Siemens process consists of three parts. In the first part, metallurgical silicon is ground up into small particles and put into a reactor, together with hydrogen chloride and a catalyst. At an elevated temperature the following reaction takes place.

$$Si + 3\,HCl \longrightarrow H_2 + HSiCl_3(g) \quad (3.5)$$

In the second part of the Siemens process, the trichlorosilane gas is cooled and liquified, and distilled to remove impurities. The third part of the Siemens process is chemical vapour deposition, and is shown in Figure 3.3. Here the trichlorosilane is evaporated and mixed with hydrogen in a reactor. The reactor contains rods of pure silicon that are electrically heated to 850-1050°C. When trichlorosilane comes into contact with the hot rods it undergoes a reaction, leading to the deposition of silicon atoms onto the rods. The chlorine and hydrogen atoms are released from the surface and return to the gas phase. This process results in the growth of a pure silicon material, with a purity of 99.9999%. The chlorosilanes and hydrogen at the exhaust can be recycled.

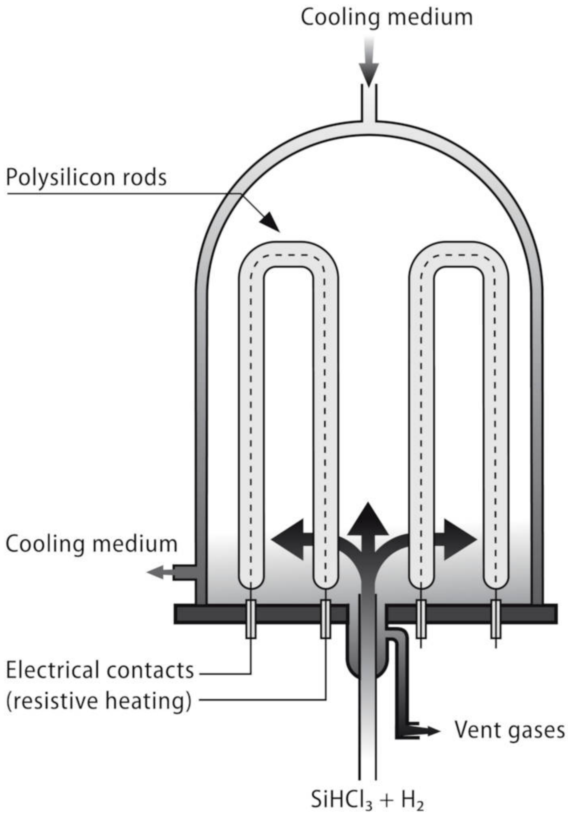


Figure 3.3: Chemical vapour deposition [29]

The next step consists of making a monocrystalline ingot, using the Czochralski processing method. The Czochralski process involves melting the polysilicon in a crucible, at a temperature of 1500°C. A seed crystal with a defined orientation (100 or 111) on a rotating shaft is dipped into the molten silicon. The molten silicon attaches to the seed crystal and takes over its orientation. The rotating seed crystal is slowly pulled upwards, continuing to form a single-crystal cylindrical ingot. The process is shown in Figure 3.4. The ingot can have a length of up to two meters, and a diameter of 200-300 mm. Argon gas is used to create an inert atmosphere, as to avoid the inclusion of impurities.

Diamond wire sawing (DWS) is used to saw the mono-crystalline into wafers [31]. A part of the silicon is lost during the sawing due to kerf losses. Around 58 µm is lost, which on a wafer of 160 µm thickness is 26%. The next steps of transforming the wafer into a PERC cell are shown in Figure 3.5.

The wafer is cleaned to remove unwanted organic particles, reduce impurities and to prevent contamination of other wafers and equipment. Liquid ammonium hydroxide (NH_4OH) and hydrogen peroxide (H_2O_2) is mixed with deionised water, wherein the wafer is cleaned for 6-10 minuted at a temperature of 80°C. A thin oxide layer could be formed, wich is why the wafer is then rinsed with a hydrofluoric acid bath to remove this layer. The wafer is then again rinsed in a mixture of hydrochloric acid (HCl), H_2O_2, and deionised water for 6-10 minuted at 80°C. This removes any metallic impurities. The thin oxide layer that may have formed can be removed with a hydrofluoric bath.

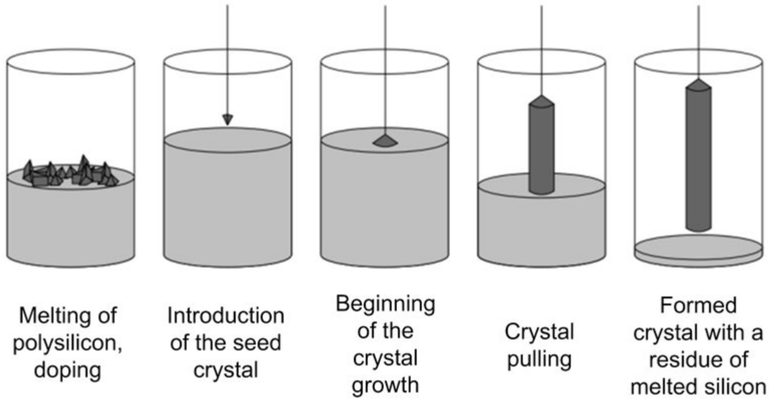


Figure 3.4: Process of fabricating a silicon ingot [30]

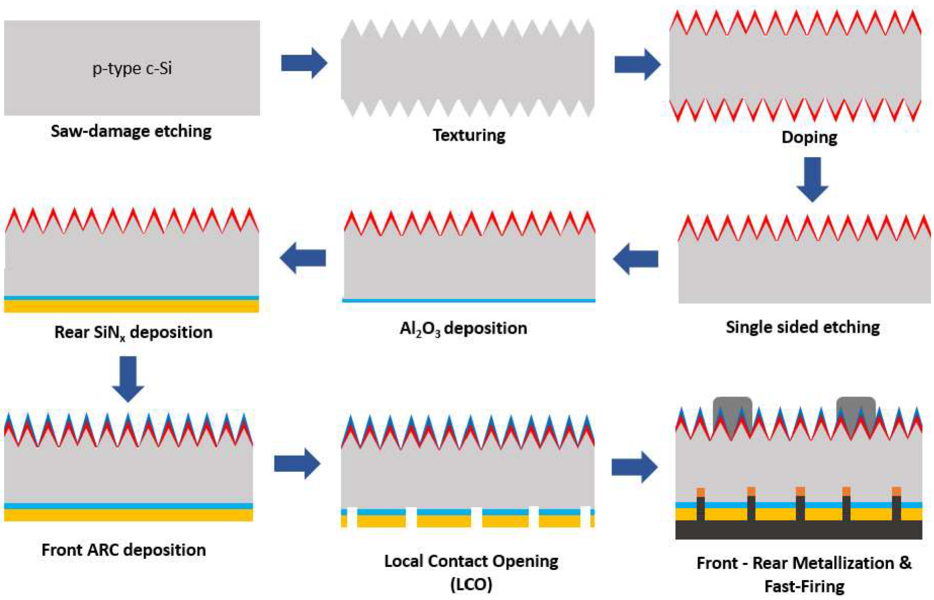


Figure 3.5: Production steps from wafer to cell

The wafer is damaged from the sawing, and needs polishing to reduce reflectivity. With DWS, around 5 µm of silicon is needed to be etched from the surface. The surface is then textured to have a random pyramid structure. This texture reduces the reflection and increases the absorption of light into the cell. The etching is done using a wet alkaline etch process. The process uses potassium hydroxide (KOH), sodium hydroxide (NaOH), or tetramethylammonium hydroxide (TMAH). This is diluted in deionised water, where the silicon, water and OH^- react as follows.

$$Si + 2\,OH^- + 2\,H_2O \longrightarrow SiO_2(OH)_2^{2-} + 2\,H_2 \tag{3.6}$$

The H_2 can form bubbles at the surface. Isopropanol is introduced to reduce surface tension and releases the H_2 gas form the surface. An alkaline etch processes is carried out at a temperatures of 70-80°C.

The next step consists of doping the front layer. This is necessary for creating a p-n junction, so electron-hole pairs can be formed. Wafers are placed on a carrier boat and placed into a furnace. Outside the furnace, N_2 gas goes through the liquid phosphorus chloride and $PoCl_3$ evaporates. The gas is moved through the diffusion tube, and reacts with O_2 as in reaction 3.7. The P_2O_5 is deposited on the surface of the wafers, and reaction 3.8 takes place. The phosphorus is absorbed into the wafer, whereas the silicon oxide layer remains on the surface. This layer is called phosphosilicate glass (PSG).

$$4\,POCl_3(g) + 3\,O_2(g) \longrightarrow 2\,P_2O_5 + 6\,Cl_2(g) \tag{3.7}$$

$$2\,P_2O_5 + 5\,Si(s) \longrightarrow 5\,SiO_2(s) + 4\,P(s) \tag{3.8}$$

The PSG layer is to be removed, using a chemical etch process. The wafer is put into a hydrofluoric acid bath for 1-2 minutes, and after it is rinsed with deionised water. During the process of diffusion, both the front and back surface of the wafer are doped with phosphorus. Since a PV cell only works with a doped layer at the front of the wafer, the back layer and side edges must be etched away.

Next a passivation layer is added on the bottom surface with the function of electronic isolation, as it reduces surface recombination. For the p-type silicon, AlOx is used for the passivation layer. On top of the passivation layers at the rear side comes the capping layer, which consists of SiNx. Plasma enhanced chemical vapour deposition (PECVD) is used for deposition of the layer. The layer works as a back reflector and reduces surface recombination.

On the front of the wafer a SiNx layer is deposited. The function of this layer if to reduce reflection and to absorb more light into the cell. It is therefore called a Anti Reflective Coating (ARC). This layer is also deposited using the PECVD tool.

The last step of producing a cell, is adding the metal contacts at both the front and the rear. At the rear side, openings are made in the passivation layer so the metal contacts are in contact with the bulk silicon. The openings are made with laser ablation and this process is called Laser Contact Opening (LCO). After this, the back layer is printed using aluminium metallization paste. At the front of the cell, silver is used to create contacts. The contacts are placed in line formation, called fingers, which are connected to perpendicular busbars. The front layer is printed onto the ARC layer, and does not make contact to the silicon layer. This process is shown in Figure 3.6.

The cell undergoes a process called firing, in which the cell is placed in a furnace of around 850°C. The silver at the front locally etches the passivation layer away and makes contact

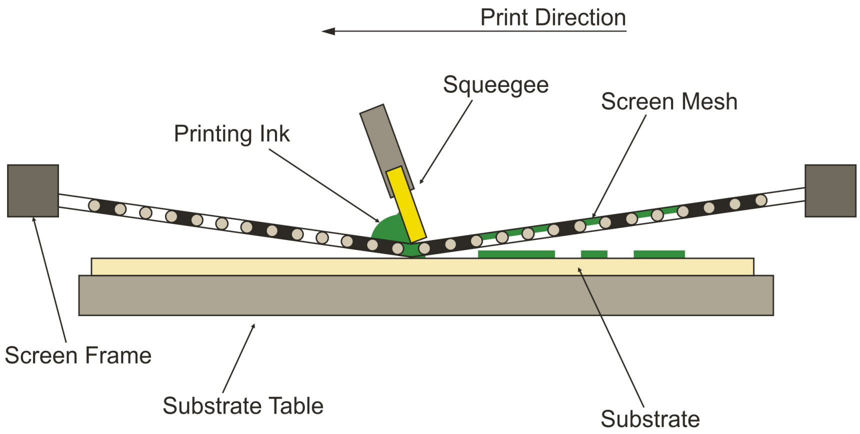


Figure 3.6: Screenprinting [32]

with the silicon. At the back of the cell, the firing causes some aluminium atoms to diffuse into the silicon, creating a local back surface field. Some silver busbars are added to the back surface for the connection between cells.

The last step of production is making the PV panel. The cells are connected in series, using copper wires. On both sides of the cells, an encapsulant layer is placed, made from ethylvinylacetate. The cells are places between solar glass at the front and polyvinylfluoride & polyethylene terephthalate sheet at the back. Finally an aluminium frame is placed around the module, completing the production process.

3.2 Goal and scope

The goal of the study starts by stating the intended application. For this study, the application will be to be used as comparison to other LCA studies of PV panels, but also to other energy sources. It will give the most up to date data of a PERC solar panel, and will be useful to show how much impact this type of sustainable energy source has compared to other sustainable energy sources.

The reasons for carrying out this study, is to show the possibility of producing PV in Europe, and the difference it has compared to production in China. This study is carried out as a fulfilment of completing a master degree.
The product system of this study is a PERC PV panel. This panel is produced in Europe, in 2022. The PV panel produces energy, so the functional unit is 1 kWh. This functional unit is most used in other PV LCA studies, and is therefore the best unit to use to compare. This functional unit can also be used to compare to other sustainable energy sources. Furthermore, the unit kWh is recommended by LCA guidelines [33].

The system boundary is shown in Figure 3.7. For each unit process the energy and materials are at the input. The emissions from each unit process are emitted to the air, water, or soil. The system is analysed from cradle-to-gate. The use phase consist of installation of Balance-of-System and maintenance, and is not included. This ensures that only the PV panel is analysed, and not the extra electrical components of a PV system. The End-of-Life of a PV panel is a fairly new topic and is still in research phase. To include this step will lead to many assumptions and reduce the quality of this study. It is therefore not included.

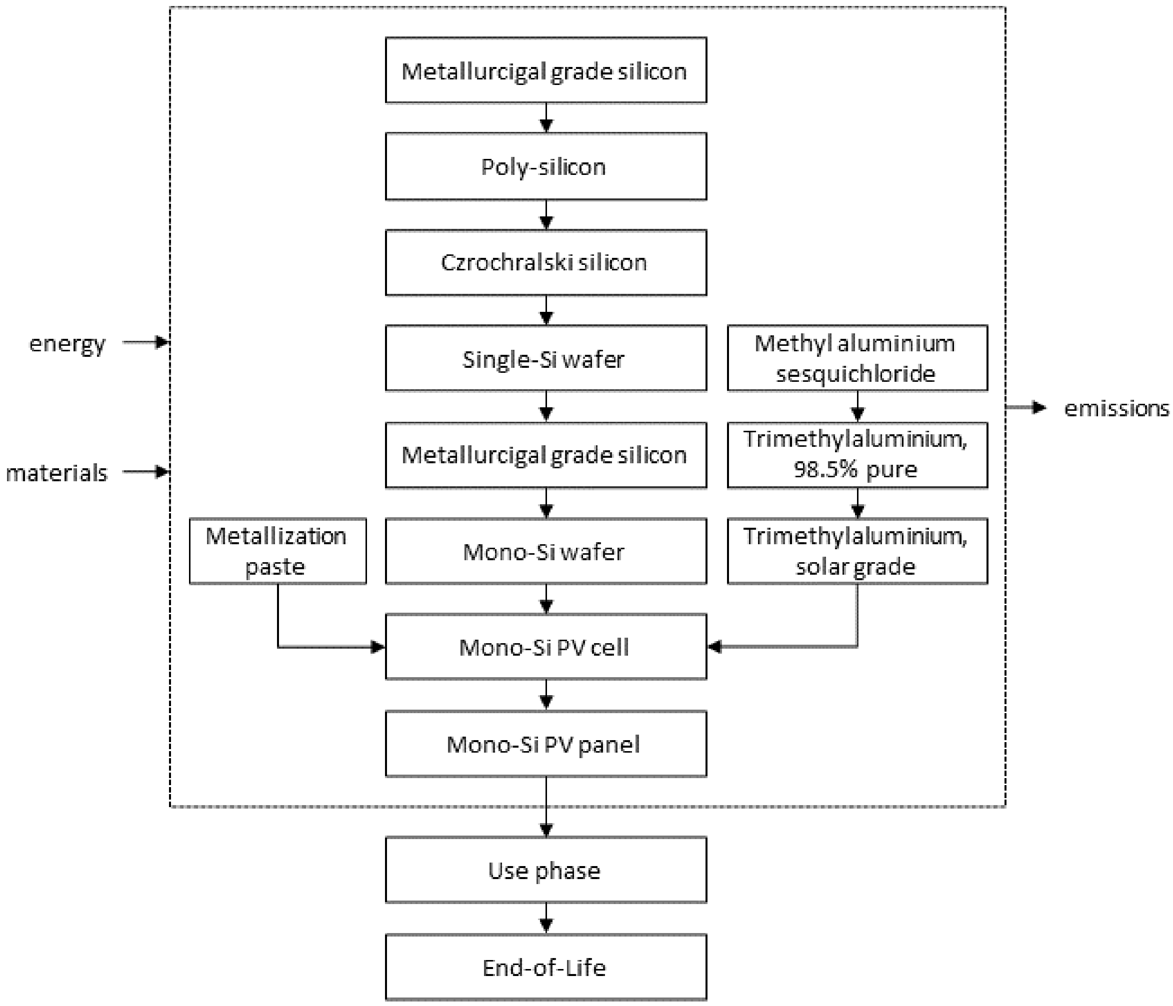


Figure 3.7: System boundary

The background processes are calculated using Industrial Design & Engineering MATerials database (IDEMAT) [24]. The database is composed of peer-reviewed scientific papers and additional LCI's made by Delft University of Technology. The IDEMAT is made to achieve a better accuracy than Ecoinvent in terms of emissions, electricity, and transport, and to provide better transparency of LCI data sources. The database has extra data on plastics, alloys, and wood species, which were lacking in Ecoinvent [24]. For materials that are not included in IDEMAT, Ecoinvent 3.8 is used. For materials that were absent in both databases, a separate LCA is found. The electricity mix of 2019 is used in IDEMAT. This is the last year where the electricity use was stable. The 2020 and 2021 data is unstable due to Covid-19, and 2022 data is unstable due to the war in Ukraine [24].

The foreground processes are calculated using Ecocosts Midpoint Table. It consists of a list of emissions, divided into impact categories with their corresponding factor of equivalent emission [24].

3.3 Life cycle inventory

Two inventories are made, one for Al-BSF and one for PERC. The PERC inventory is then modified with data from 2021, 2022, 2023, and 2030 to show the developments of last year and upcoming years. For the inventory for an Al-BSF PV panel, the inventory from IAE Photovoltaic Power Systems Programme (PVPS) is used [19]. The data concerns production in 2018 and can be found in the supplementary information.

The second inventory is from Ecoinvent 3.8 and from Müller, at Fraunhofer ISE [20]. The inventory is made on a PERC cell that is produced in Europe in 2021. The data is then adjusted to different years using the PV roadmap for 2021 and 2022 [34][35]. The PV roadmap contains speculation on future trends, which are used to make an inventory for PERC production in 2023 and 2030. In 2030 PERC cell will only be 20% of the total market share, so the 2030 prediction is not to be used for the whole PV market.

The difference in inventory between the Al-BSF and PERC cell is mainly due to difference in production process, but also due to increased efficiency in production, and change in materials. For the production of metallurgical grade silicon, the amount of wood chips used is reduced by 99%. The next step in production for an Al-BSF cell is solar grade silicon with the modified Siemens process, while PERC uses a Siemens process to produce poly-silicon which uses more electricity and more heat. For the Czochralski process, most of the materials used are reduced by more than half. For the wafer production, less electricity is used by increased efficiency, as well as less materials. The production of the cell has the biggest difference, since it is a different process and other materials are used. The last step of making the PV panel has a difference in amount of materials used, such as a 10% reduction in glass and 30% reduction in aluminium.

The production of PERC cells have a high rate of innovation. The amount of consumption of poly-silicon per M10 wafer has decreased from 17.5 g in 2021, to 17 g in 2022. It is expected that this will decrease further to 16.5 g in 2023, and to 13 g in 2030. This is achieved by reducing the kerf loss and reducing the thickness of the wafers. The kerf loss in 2021 and 2022 is 60 µm and 57 µm respectively. This will reduce to 55 µm in 2023 and 45 µm in 2023. The wafer thickness is 170 µm in 2021 and 160 µm in 2022, and expected to be 155 µm in 2023 and 140 µm in 2030. These factors all influence the amount of silicon use, and are included in the inventories for 2022, 2023, and 2030.
The amount of silver used for metallization paste for PERC in 2022 was around 10% of the

world silver supply [27]. It is an expensive metal, and efforts are made to reduce the silver consumption to reduce the costs of the PV panel. The amount of silver per cell was 95 µg in 2021 and 85 µg in 2022, and is expected to be 75 µg in 2023 and 55 µg in 2030. The amount of alumiunium is brought down from 1000 µg per cell in 2021 to 950 µg. The downward trend is expected to continue with an amount of 900 µg in 2023, and 790 µg in 2030.

Next to reducing the amount of metals in the metallization paste, the amount of metallization paste is also reduced. In 2021 a finger width of 33 µm was used, in 2022 30 µm. In 2023 the finger width will be 27 µm and in 2030 18 µm.

In 2021 copper ribbons is the main technology for interconnection between cells. The market has changed and copper wires are now the most used technology and will remain the dominating form of interconnetion. The diameter of the wires is 305 µm, and will be 295 µm in 2023 and 240 µm in 2030. The glass thickness in 2021 is 3.2 mm, and is reduced to 2-3 mm in 2022. No absolute value was given, so only a minimal reduction is used for calculation.

The PERC module used for the inventory is from 2022, since this module has the most recent data without assumptions. The parameters used for the models are shown in Table 3.1. The inventory can be viewed in the appendix.

Table 3.1: Parameters for Al-BSF, and PERC for 2021, 2022, 2023, and 2030.

Parameters	Al-BSF	PERC 2021	PERC 2022	PERC 2023	PERC 2030	Ref.
lifetime expectancy [years]	25	30	30	30	30	[19][33]
Module efficiency	19.5%	19,79%	21.3 %	21.7%	23.2%	[19][20][36] [37][38]
Degradation per year	0.5%	0.5%	0.5%	0.5%	0.5%	[39]
glass thickness [mm]		3.2	2 - 3	2 - 3	2 - 3	[20][35]
Cell type	M3	M6	M10	M10	M10	[19][20][35]
Wafer thickness [µm]	170	170	160	155	140	[19][34][35]
Kerf loss [µm]	65	60	57	55	45	[19][20][35]
Poly-silicon consumption [g/wafer]	15	17.5	17	16.5	13	[19][35]

For the calculation of the inventory, the following assumptions are made.

- The damage of coke is given in kg, so a factor of 28.2 is applied to transform it to MJ [40].
- Electricity from IDEMAT is in MJ, and is converted to kWh.
- Wood chips have a negative impact, since this materials comes from wood waste.
- The production of ceramic tile is a combination of Stoneware and Glaze.
- Aluminium wrought alloy is calculated by combining Aluminium and Forging aluminium.

- ’Chemical, organic’ is a mixture of thirteen chemicals: Acetic Anhydride with different production processes, Acrylonitrile, Benzene, Dipropylene glycol monomethyl ether, Ethanol, Pentane, Phenol, Propylene, Styrene, Toluene, and Xylene.
- ’Solvent, organic’ is a mixture of Styrene, toluene, Xylene, Ethylene glycol, and Methanol.
- Corrugated board is de combination of Brown paper, and Corrugated board box making.
- Silicone rubber is used for Silicone product.
- For solar glass, ’glass cladding and windows’ is used.
- For glass fibre reinforced plastic, PA66 is used.
- Low density polyethylene packaging film is converted from m2 to kg, using a density of 42.7 m2/kg [41].
- For particleboard a density of 200 kg/M2 is used [42].
- Zeolite powder is not present in IDEMAT, so a separate LCA study is used [43].
- For high pressure natural gas a density of 180 kg/m3 is used [44].
- Ultrapure water is calculated with deionised water.
- Acrylic acid is not included in IDEMAT and Ecoinvent, so a separate study is used [45].
- The density of a conveyer belt is 15/m2, so for a belt with a width of 1m, 15kg/m is used for calculation [46].
- A multi storey building has an average amount of metal of 54 to 55 kg/m2 [47].
- A blast furnace is around 1.00E7 kg [48].

3.4 Life cycle assessment

The categories for the assessment phase are listen in Table 3.2, including the indicators and equivalent emissions. This list of categories are taken from IDEMAT, and are the recommended categories from the LCA guidelines [33].

Table 3.2: Categories and their equivalent something

Impact category	Indicator	Unit
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_{2eq}
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}
Human health, cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Human health, non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Particulate matter	Impact on human health	disease incidence
Ionising radiation, human health	Human exposure efficiency relative to U-235	kBq U-235
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg $NMVOC_{eq}$
Acidification	Accumulated Exceedance (AE)	mol H^+_{eq}
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e
Land use		points
Water use	User deprivation potential (deprivation-weighted water consumption)	M3
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

The first category is **climate change**, with the indicator Global Warming Potential (GWP). The equivalent unit used for this category is one kg of carbon dioxide. The gases in this category are called Greenhouse Gases, which absorb energy and warm up the earth's atmosphere. The value of the emission is based on the amount of energy it absorbs, and how long the gas remains in the atmosphere [49]. For this category the impact of 100 years is used, since the lifetime of the equivalent emission (CO_2) is 100 years [50]. This indicator is advised by IEA Task12 guidelines [33].

The second category is **ozone depletion**. The indicator is Ozone Depletion Potential (ODP), with an equivalent emission of trichlorofluoromethane (CFC-11). The ozone layer acts as a protection layer for humans and the biospehere from UV light. Ozone is continuously produced by oxygen and UV light, and destructed by oxygen, hydrogen radicals, nitrogen oxide radicals, and halogen radicals. Without human interaction, there is a natural balance between production and destruction. However, by human influence, an abundance of destructive chemicals are in the stratosphere and causes thinning of the ozone layer [51].

The third and fourth categories are **human toxicity**, both with an equivalent emission of Comparative Toxic Unit for humans (CTUh). The categories are divided into cancer, and non-cancer. The unit CTUh indicates the increase in amount is disease cases per kg emitted. The emissions are ingested or inhaled via air pollution or water pollution, causing an increase in morbidity. The cancer category is seen as more reliable, since non-cancer cases must be above a certain treshold to be taken into account [52].

The fifth category is **particulate matter (PM)**. This category uses the indicator Impact on human health, and an equivalent emission of disease incidence. particulate matter is solid particles and aerosols. Due to the small size of the particles, it is easily inhaled and ends up in the lungs or bloodstream, causing health problems [53]. PM10 stand for particles smaller than 10 microns. PM2.5 stands for particles smaller than 2.5 microns, and are part of PM10. When inhaling particulate matter, PM10 stays in the larger airways, while PM2.5 gets deep into the lungs. The particles cause tissue damage and lung inflammation [54].

The sixth category is **ionising radiation**, with indicator Human exposure efficiency relative to U-235. The equivalent emission used is Uranium-235. This category indicates radiation. Radiation can come from natural sources found in air, water, and soil, but also from natural radiation from cosmic rays. Another source is human made, and includes nuclear power stations and x-ray machines. Some production processes produce radiation. Exposure to radiation results in tissues damage and organ damage [55].

The seventh category is **photochemical ozone formation**, with the indicator Tropospheric ozone concentration increase. The equivalent emission is non-methane volatile organic compounds (NMVOC). The emissions in this category create ozone in the lower troposhere. This would be beneficial at stratosphere, but at ground level it causes damage to humans and vegetation. It induces respiratory damage in humans, and crop damage in vegetation [56].

The eight category is **acidification**. The indicator is Accumulated Exceedance, and the equivalent emission is H^+. The pollution of materials emitted in this category cause a reduction in pH level in soil and water. The environment becomes more acidic, which causes a decrease in forests and marine life [57]. The emissions NH_3 and NO_2 are not counted in this category to avoid double counting. They are placed in the category eutrophication, since this is a bigger issue in Europe for these emissions [24].

The ninth category is **eutrophication, terrestrial**, with indicator Accumulated Exceedance, and equivalent emission of mol N. Eutrophication is the abundance of nutrients, primarely nitrogen and phosphorus. On land it can cause a growth of species that thrive on high nitrogen levels, loss in other sensitive species, and change in habitat by homogenisation of vegetation [58].

The tenth category is **eutrophication, freshwater**. The indicator is Fraction of nutrients reaching freshwater end compartment, and the equivalent emission used is P. In this category, the discharge of nutrients into the freshwater is evaluated. With too high levels of nutrients, algea starts to grow, spread and block sunlight in the water body. The bacteria that decompose dead algae consume oxygen, creating an uninhabital environment for plants, fish, and other aquatic organisms [59].

The eleventh category is **eutrophication, marine**, with indicator Fraction of nutrients reaching marine end compartment, and equivalent emission N. The eutrophication effect in marine is similar to freshwater, but with a different outcome. The overabundance of nutrients cause high amounts of algea and low oxygenated waters. The decomposing of algea produce high levels of carbon dioxide, which lowers the pH level of the water. This acidification causes problem with producing shells and skeletons in calcifying organisms. This in turn lowers the amount of bacteria that reduce nutrients, and causes a viscious circle [60]. Other marine life is affected by acidification by the decreasing ability to detect predators. Both factors influence the marine food chain, and reduce fisherman catch [61].

The twelfth category is **freshwater ecotoxicity**. The indicator is 'Comparative Toxic Unit for ecosystems', and the equivalent emissions is CTUe. Ecotoxicity represents the effect of chemicals on organisms. The effects of toxic chemicals can cause loss in biodiversity and extinction of species. The category freshwater is used, since water is the main body used for discharge of chemicals [62].

The next category is **land use**, with the equivalent emissions in points. This category includes the use of land, but also the transformation of land use. The amount of land use can have an effect on the biodiversity. For the calculations in this study, only the land-use of agricultural data is taken into account. The calculations are taken from IDEMAT, where the growing are of agricultural land is seen a the main cause for degradation of biodiversity.

The fourteenth category is **water use**, with an equivalent emission of m3. Water scarcity is spreading around the world, impacting the amount of drinking water and food production. The extraction of water also causes harm to other lifeforms and to biodiversity. Climate change is amplifying the water scarcity, making this an important impact category to include in an LCA [63]. This category is only on the extraction of water and not the pollution, since this is covered by other impact categories. Water is only taken into account if it is absorbed into the product. If it flows back into nature, it is not included into the calculation [24].

The final category is **resource use**. This category is divided into fossil and mineral & metals. Fossil use has the equivalent emission of MJ, the mineral & metals use has an equivalent emission of Sb. The value given to emissions is not only on the amount of materials extracted, but also on the scarcity of the material. The amount of resource used can be decreased by using recycled materials [64].

Some materials are calculated using another equivalent emission, and have to be converted to the equivalent emission used in this study. The factors used for this are shown in Table 3.3.

Table 3.3: conversion factor

Impact category	source unit	target unit
Ionising radiation	1.4 kBq Co-60	1.7 kBq U-235 [24]
Photochemical ozone formation	1 kg NOx	1 kg NMVOC [24]
Photochemical ozone formation	1 kg ethene	1.69 kg NMVOC [24]
Particulate matter	1 kg PM2.5	0.000629 disease [24]
Human health, non-cancer	1 kg 1,4-DCB	5.42E-08 CTUh [65]
Human health, cancer	1 kg 1,4-DCB	1.81E-07 CTUh [65]
Acidification	1 kg SO2	1.31 mol H+ [24]
Eutrophication freshwater	3.06 kg PO4	1 kg P [24]
Ecotoxicity	1 kg 1,4-DCB	9.83E+02 CTUe [65]
Land use	1 point	1 m2 [24]
Resource use, mineral & metals	1 kg Cu	0.572 kg Sb [24]

The environmental impact per endpoint category is calculated by assigning a factor to each midpoint category. These factors are displayed in Table 3.4. The midpoint categories are added up to come to the total impact per endpoint category.

Table 3.4: Midpoint to endpoint conversion factors [66].

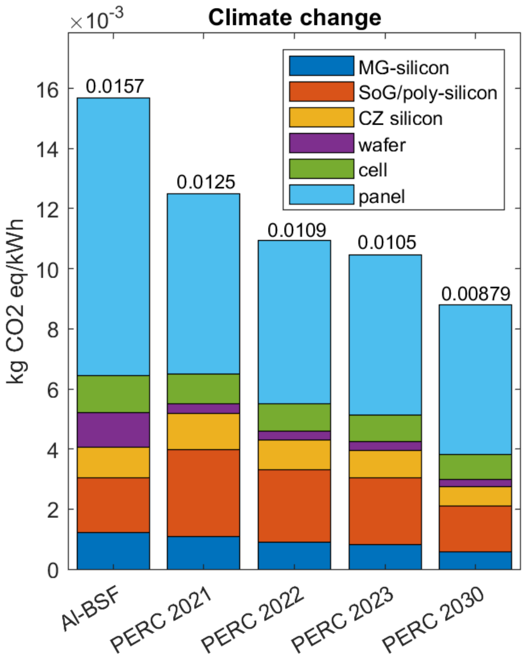
Midpoint category	Factor	Endpoint category
Climate change	9.28E-7	Human health [DALY]
Ozone layer depletion	5.31E-4	
Human health, non-cancer	4.21E+00	
Human health, cancer	2.81E+00	
Particulate matter	1.00E+00	
Ionising radiation	7.00E-9	
Photochemical Ozone formation	9.10E-07	
Water use	2.22E-6	
Climate change	2.80E-9	Ecosystem health [species/year]
Acidification	1.62E-7	
Eutrophication, terrestrial		
Eutrophication, freshwater	6.71E-7	
Eutrophication marine	1.70E-9	
Ecotoxicity	7.07E-13	
Land use	8.88E-9	
Water use	1.35E-8	
Resource use, fossil	0.2	Resource availability [€]
Resource use, mineral & metals	4.04E-1	

Chapter 4

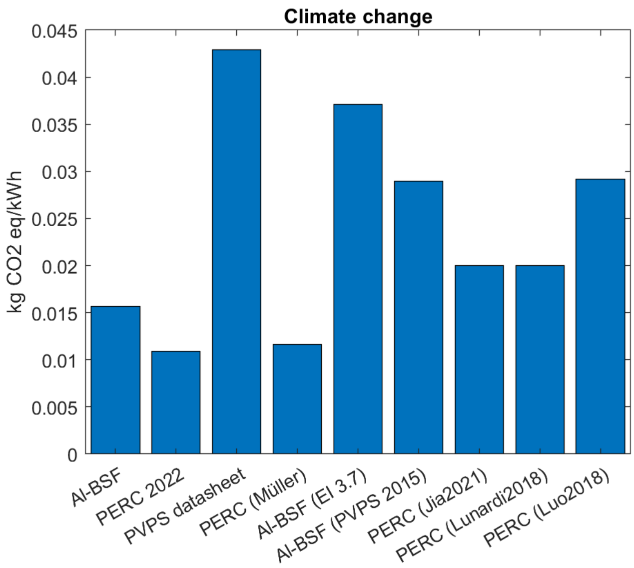
Results

This chapter shows the results of the the life cycle impact assessment. Per impact category the results are shown of the Al-BSF cell and the PERC cell, including the different years. Next to that is a figure showing the results compared to other studies. These studies are further explained in the introduction.

4.1 Climate change



(a) Results per production step



(b) Comparison between studies

Figure 4.1: Results on climate change

The most used category to calculate environmental impact is climate change. In Figure 4.1a the results are shown of this study. There is a clear difference between the production of an Al-BSF and a PERC cell. The biggest impact is in the last production step, where the final PV panel is fabricated. In this step, the aluminium alloy and the solar glass are the biggest contributors in terms of CO_2.

The decline in wafer production is due to less electricity consumption, a decrease in the use of a water factory, and less consumption of alkylbenzene sulfonate. This material has one of the biggest impact in wafer production, and is reduced by 85% for the production of a PERC cell.

The second production step step has an increase in environmental impact. For PERC production, poly-silicon is used. In the production of an Al-BSF cell, solar grade silicon is used. This is silicon with a lower purity, and uses less energy to produce. Since electricity and heat have the biggest impact in this stage, it is only logical that there is an increase in this production step going from Al-BSF to PERC.

When comparing the PERC module of this study to the PERC module by Müller, only a difference of 6% is found in terms of climate change. The Al-BSF modules have the highest impact, and second are the modules made in China and Singapore. The Al-BSF and the PVPS2015 study use the same inventory, but have a different outcome. The PVPS 2015 is calculated using SimaPro, while this study used IDEMAT. The production location used for PVPS2015 is a combination of Europe and China.

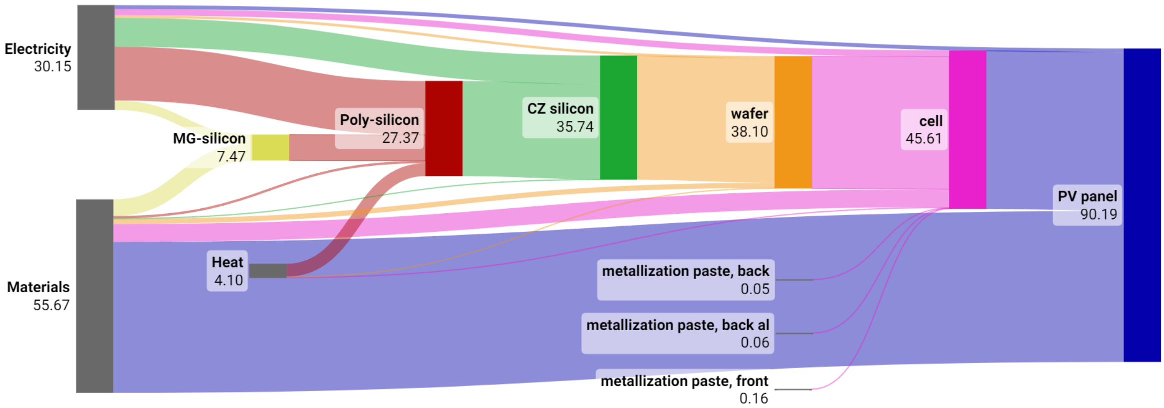


Figure 4.2: Sankey diagram of kg CO_2/kWh

Figure 4.2 shows the sankey diagram of the amount of CO_2 per production stage. This figure shows how much CO_2 is originated from electricity, heat, or materials. However, the materials that are used from the IDEMAT database have the electricity and heat already incoroprated. This means that this graph does not show the total amount of electricity and heat, but only the amount that is used during the production steps of the PV panel.

The largest consumption of electricity is during the Siemens process, where poly-silicon is made. The second biggest electricity consumption is during the Czochralski process. The total amount of electricity use produces 33% of the total CO_2. With a share of 1/3, the electricity mix becomes a quite important factor in how much is emitted. If an electricity mix with more renewable sources is used, the impact of the PV panel production goes down.

4.2 Ozone depletion

For ozone depletion, a big difference is spotted in the Czrochralski process. In the inventory for Al-BSF, nitrogen oxides are emitted to the air, and is responsible for 99% of the total damage. This emission is not present in the PERC inventory. The second biggest impact is caused by nitric acid, which is reduced by 88% in PERC production.

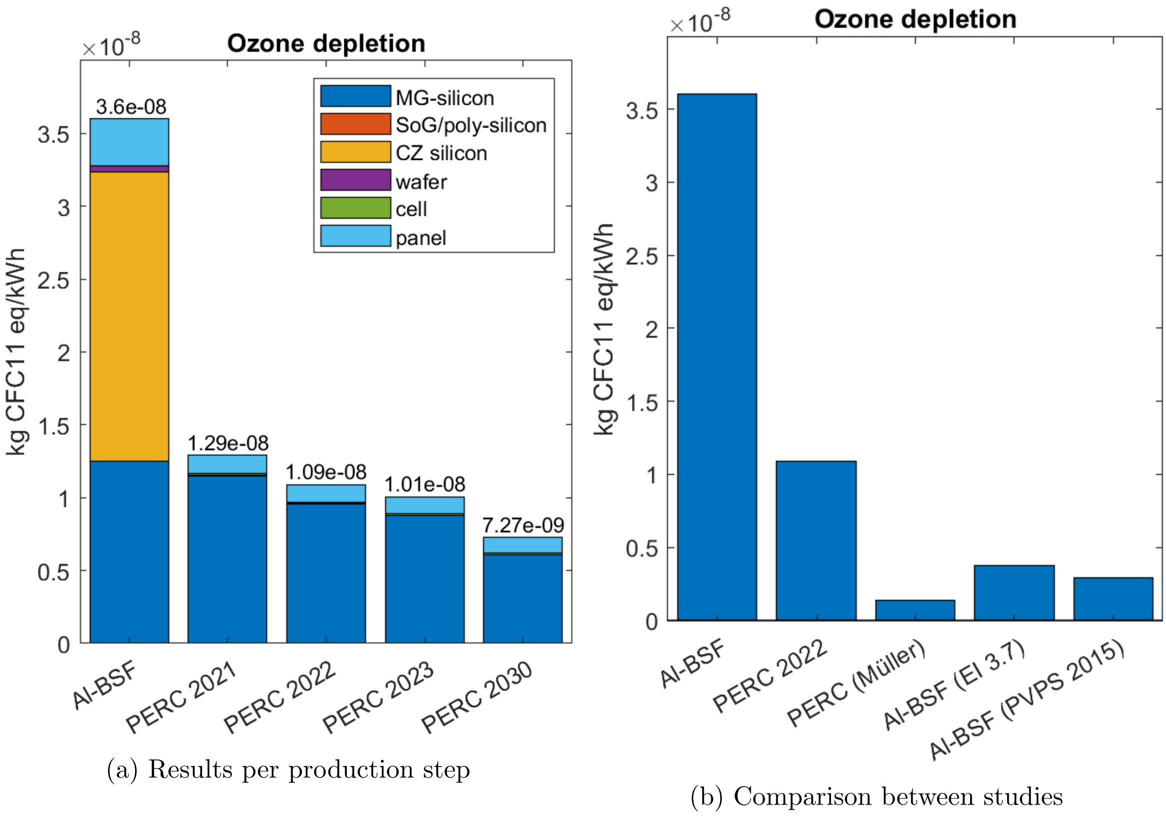


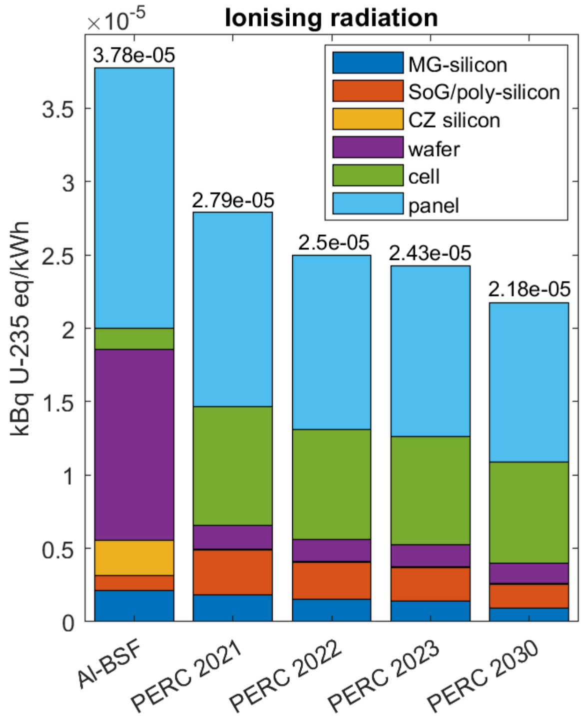
Figure 4.3: Results on ozone depletion

For the PERC cells, the biggest impact is in the metallurgical grade silicon production process. Again, nitrogen oxide is responsible for 99% of the total damage. The increase in damage from Al-BSF to PERC is not by difference in production, but because less silicon is used for producing an Al-BSF wafer.

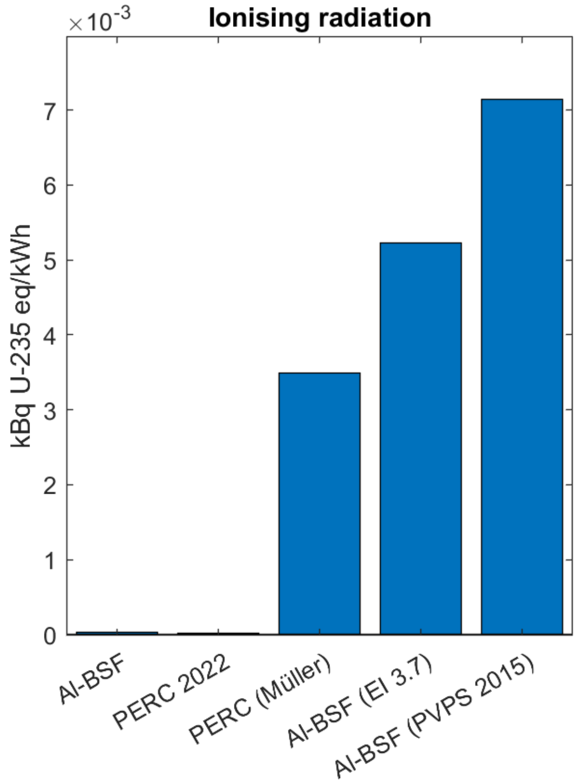
The amount of ozone depletion for the PERC cell is three times higher than the other studies. Without the nitrogen oxides as emissions during the production stage of the metallurgical grade silicon, the PERC cell would be around the same value of the other studies. The same is for the Al-BSF cell in this study, where the majority of ozone depletion comes from the production of metallurgical grade silicon.

4.3 Ionising radiation

During the production of a wafer for Al-BSF, deionised water is used, which is the biggest contributor to ionising radiation. For the production of PERC, softened water is used which has only a fraction of the damage. The second biggest impact is the water factory, which is half the use of PERC to Al-BSF. Furthermore the reduction of heat and alkylbenzene sulfonate reduces the amount of ionising radiation for the wafer process for PERC even more.



(a) Results per production step



(b) Comparison between studies

Figure 4.4: Results on ionising radiation

For producing solar grade silicon, less heat is used than for producing poly-silicon. The increase use of natural gas can be seen in the increase in poly-silicon from Al-BSF to PERC. The increase of ionising radiation in cell production is due to the use of water. For Al-BSF, only tap water is used. For PERC softened water and deionised water is used, both with high values of ionising radiation.

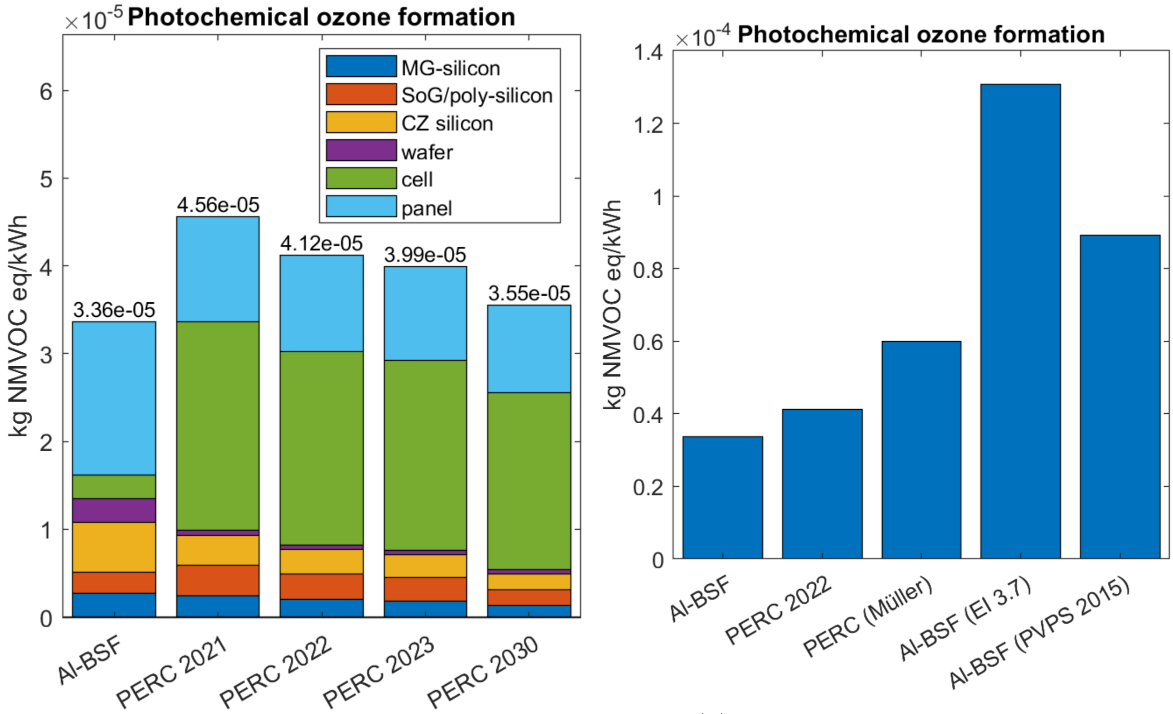
The results of this study are very low compared to the other studies. Both the inventories of this study do not contain materials with radiation properties. The only amount of ionising radiation comes from materials and electricity found in the IDEMAT database.

4.4 Photochemical ozone formation

The increase of photochemical ozone formation from producing solar grade silicon to producing poly-silicon is due to the increase in electricity. Electricity has the biggest impact in this process, and higher use can be seen in the Figure 4.5a.

For production of the single crystalline ingot, ceramic tiles have the biggest impact on photochemical ozone formation. From Al-BSF to PERC, the use of ceramic tiles is reduced by more than 60%. The second biggest impact in this process is caused by the emission of nitrogen oxides to air. In the inventory for PERC, no nitrogen oxides are emitted.

The decrease in wafer production is due to the decrease in alkylbenzene sulfonate, electricity, and water factory. The material dipropylene glycol monomethyl ether is not used in the PERC inventory.



(a) Results per production step

(b) Comparison between studies

Figure 4.5: Results on photochemical ozone formation

The biggest difference between Al-BSF and PERC is in the cell production process. The emission of NMVOC causes the largest amount of photochemical ozone formation. For PERC 150 times more NMVOC is emitted during cell production, causing the rise in ozone formation.

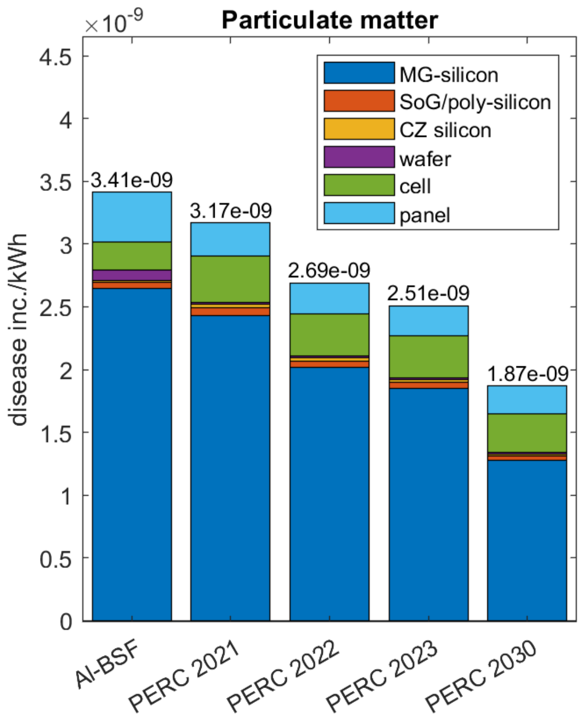
The results of this study are lower than the other studies shown in Figure 4.5b. This could be due to the calculated electricity. For IDEMAT the electricity data is more up to date than for Ecoinvent. Recent electricity mixes use more sustainable energy sources, which leads to lower emissions. The use of IDEMAT can therefore lead to lower emissions in this category where electricity is a large contributing factor.

4.5 Particulate matter

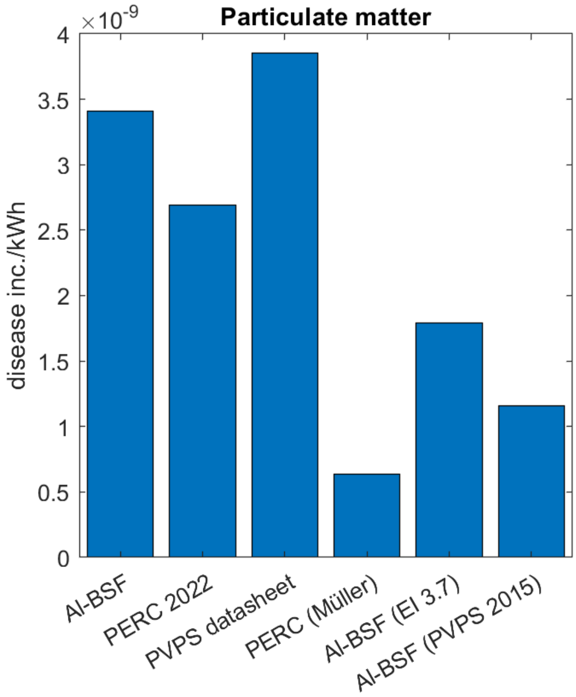
The largest emission of particles is in the process of making metallurgical grade silicon. In this process, the biggest contributors are petroleum coke, charcoal, and hard coal.

The increase in particulate matter in cell production is caused by particulates <2.5 µm emitted to air. This emission is not in the inventory for Al-BSF.

The difference between this study and the others studies is mostly the use of coke and petroleum coke in the metallurgical grade silicon production process. Without these two materials, the results would be around the value of the study done by Müller.

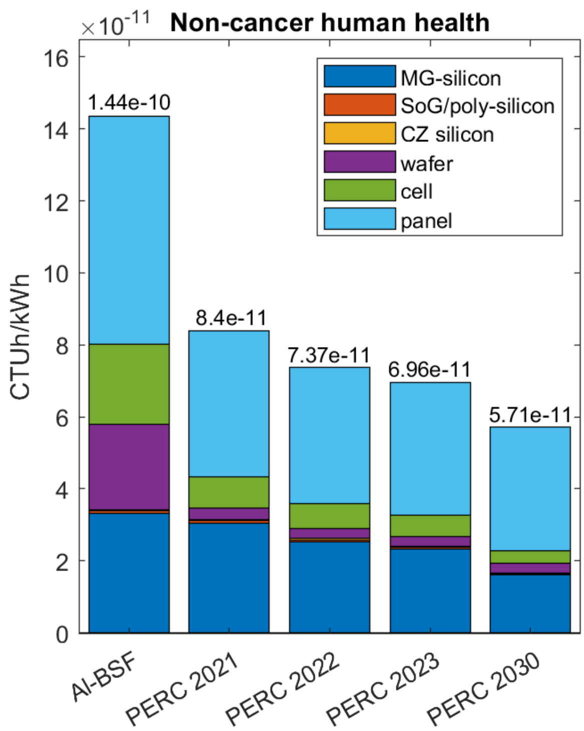


(a) Results per production step

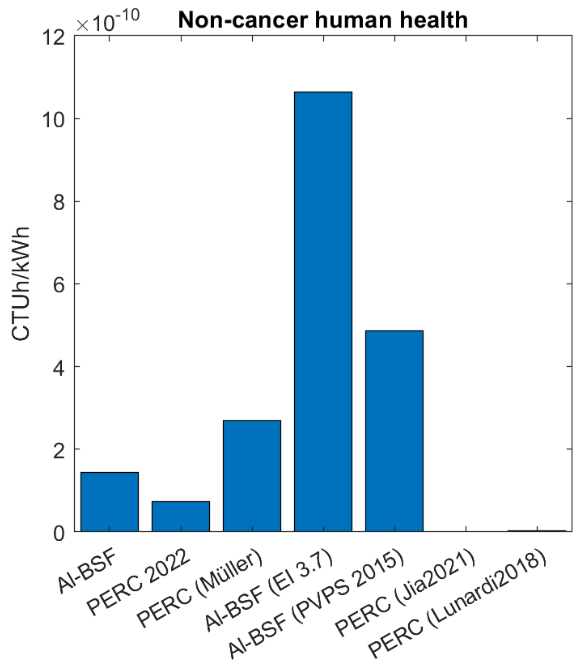


(b) Comparison between studies

Figure 4.6: Results on particulate matter



(a) Results per production step



(b) Comparison between studies

Figure 4.7: Results on human health, non-cancer

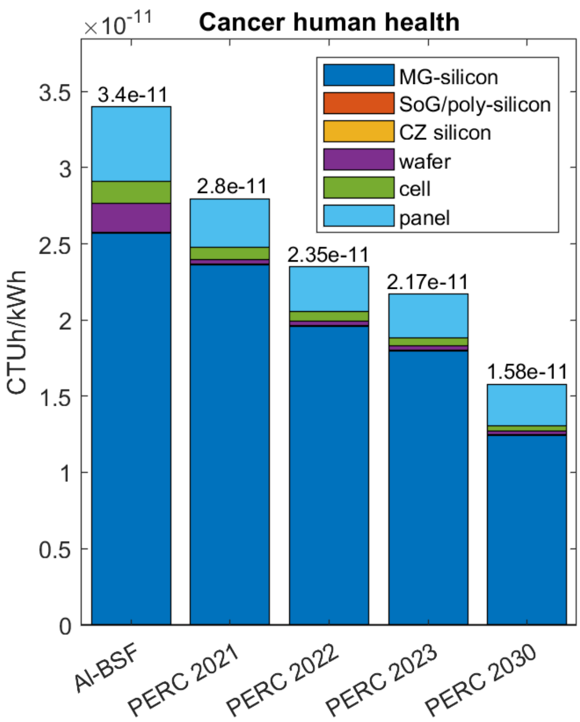
4.6 Human health, non-cancer

The biggest difference for non-cancer human health between Al-BSF and PERC is the wafer production stage. The largest contributor in Al-BSF wafer production is dipropylene glycol monomethyl ether, which is not used in the PERC inventory. The second biggest contributor is water factory, where the PERC inventory uses only half the value than Al-BSF.

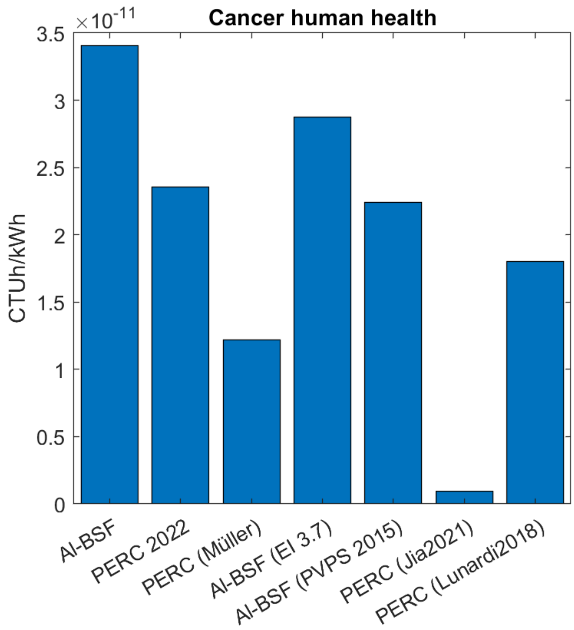
The amount of silicon used for a wafer is lower than for PERC, so the share of the impact of metallurgical grade silicon production is lower.

The results of all studies are quite far apart. The Al-BSF results from Ecoinvent 3.7 are more than 7 times higher than the results of Al-BSF in this study. The results from Jia is 67 times smaller than this study, and the results from Lunardi are 10^5 lower than the PERC cell of this study.

4.7 Human health, cancer



(a) Results per production step



(b) Comparison between studies

Figure 4.8: Results on human health, cancer

For human health (cancer), the biggest impact is in producing metallurgical grade silicon. The production of metallurgical silicon is the same for all cells, but the quantity of used metallurgical grade silicon differs. That is why the amount of impact of of MG-silicon varies per PV panel.

The result of Al-BSF of this study is slightly higher than the other Al-BSF results, and the results of PERC of this study is slightly higher than the other results of PERC studies. However, they are all in the same range, with the exception of the study of Jia.

4.8 Acidification

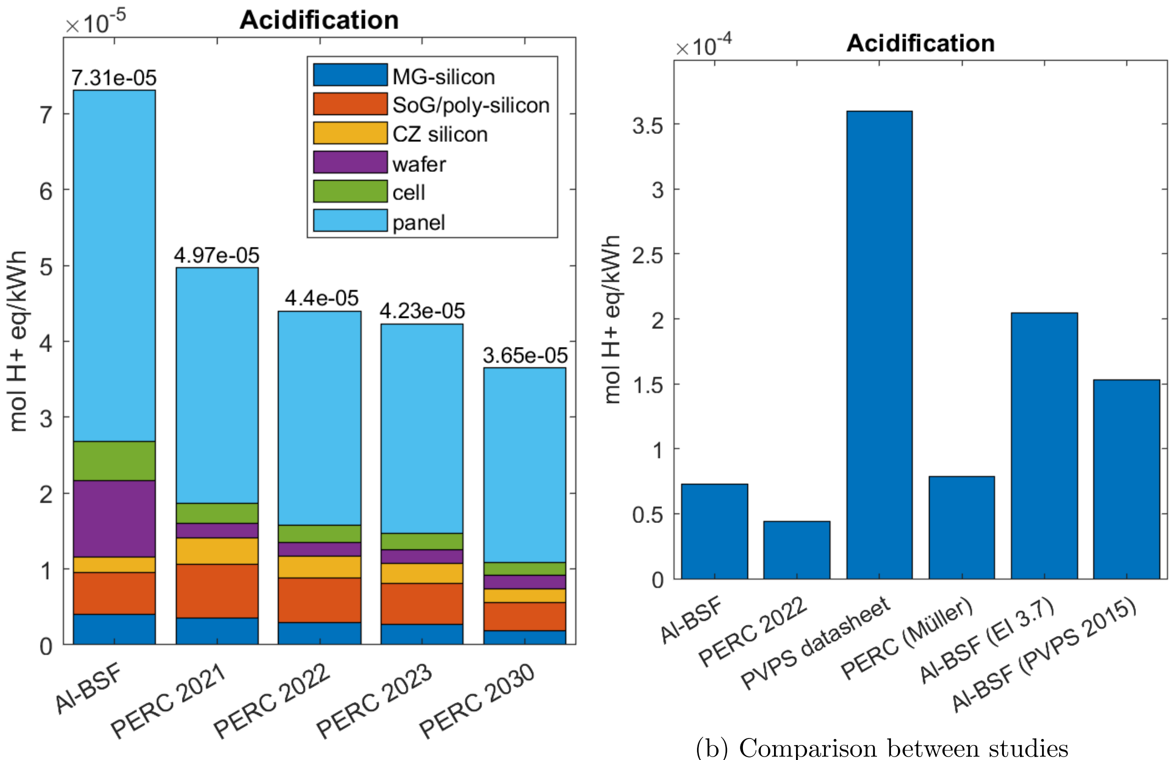


Figure 4.9: Results on acidification

The big decrease in acidification in the wafer production process can be attributed to the use of alkylbenzene sulfonate. This material is the biggest contributor to acidification in both type of cells, and so the decrease of materials results in a decrease of acidification.

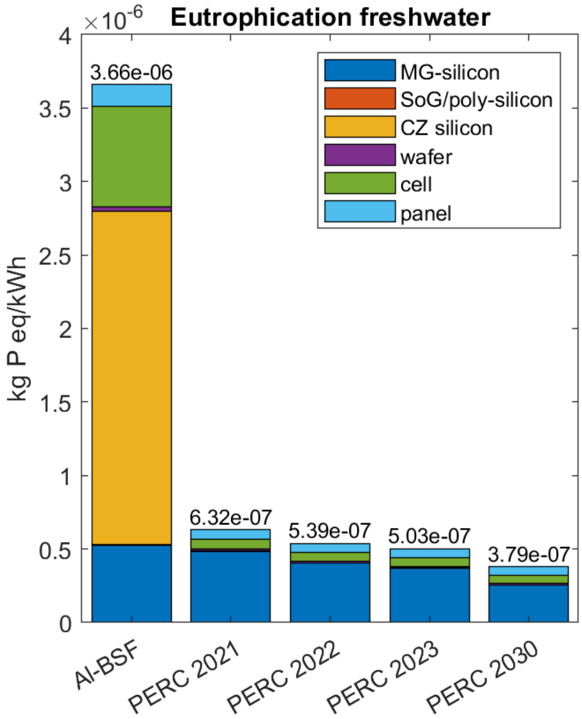
The acidification in the panel production comes mainly from the aluminium alloy. The next three biggest factors are solar glass, electricity, and ethylvinylacetate (EVA). All four of the materials are less used when making a PERC panel, therefore reducing acidification of the process.

The results of this study are in the same range as the result of the study done by Müller. The other three studies are all Al-BSF type cells with more outdated data.

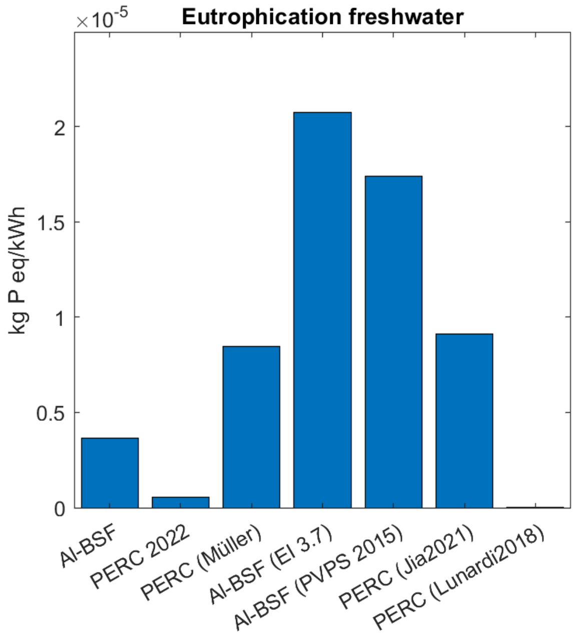
4.9 Eutrophication, freshwater

Eutrophication has a big difference between the two types of cells. For the Czochralski process, the Al-BSF inventory includes the emissions nitrogen oxides and nitrate. These emissions with the biggest impact are not in the PERC inventory, causing a large difference. The biggest impact in the PERC cell is nitric acid. This material is also used for Al-BSF, and it is reduced by 99% for the PERC inventory.

The results of the Al-BSF cell are 5 tomes lower than the other Al-BSF studies, the result of the PERC is ten times lower than the PERC studies. The outlier is Lunardi which is 24 times lower than this study Passivated Emitter and Rear Cell (PERC) cell.



(a) Results per production step



(b) Comparison between studies

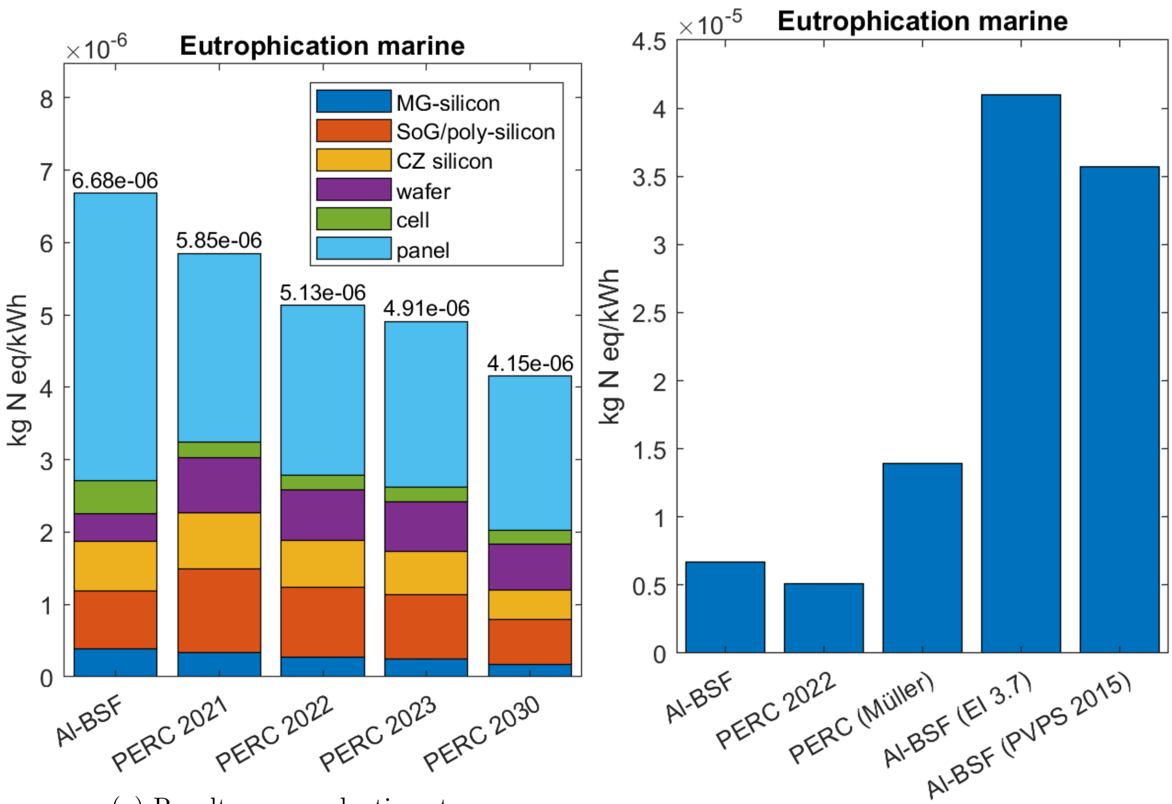
Figure 4.10: Results on freshwater eutrophication

4.10 Eutrophication, marine

For the production of solargrade silicon and poly-silicon, electricity is the largest contributor to marine eutrophication. Producing poly-silicon uses more electricity, so the PERC cell has more marine eutrophication in this production step.
During the Czochralski process, nitrate is emitted in the Al-BSF inventory, and nitrogen in the PERC inventory. This difference causes the marine eutrophication to be larger for a PERC cell.

The biggest contributing factor to marine eutrophication for panel production is aluminium alloy, the solar glass, and ethylvinylacetate. The amount of all three are significantly reduced for the PERC cell, so the effect on marine eutrophication is also reduced.

The results for this study are 1.5 times lower than the results from the study of Müller. This difference is smaller than the difference between the study of Müller and Ecoinvent 3.7 & PVPS 2015.



(a) Results per production step

(b) Comparison between studies

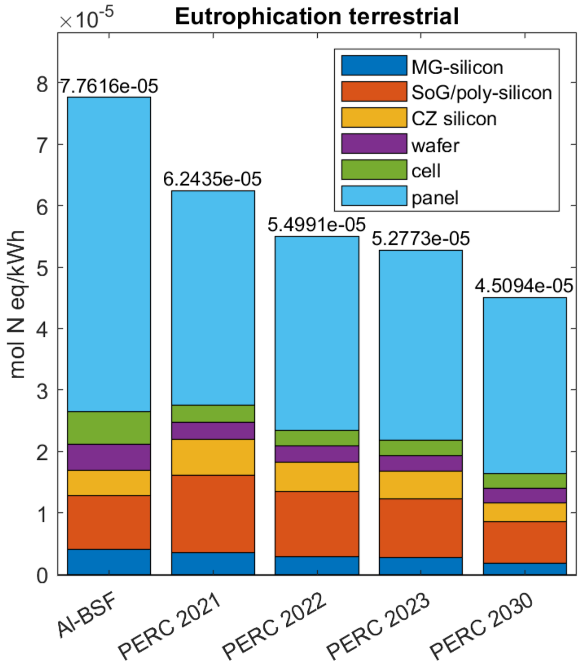
Figure 4.11: Results on marine eutrophication

4.11 Eutrophication terrestrial

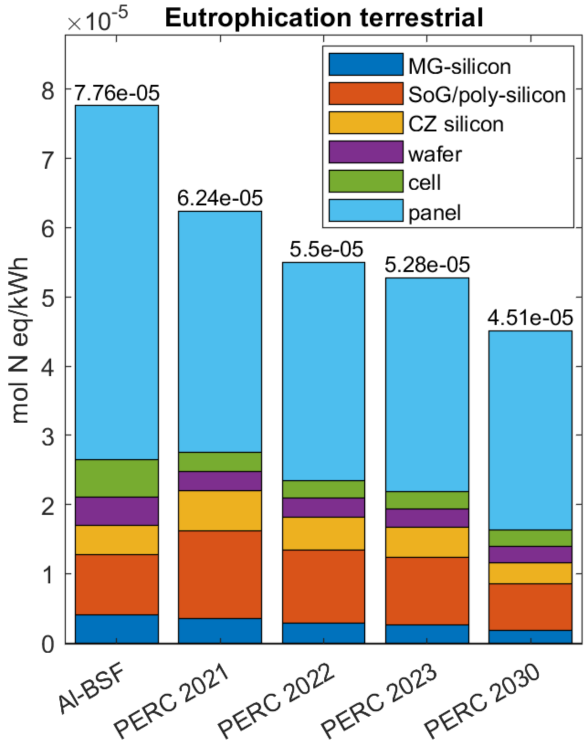
The production of the panel has the biggest impact on terrestrial eutrophication. In this process, the biggest contributors are the aluminium alloy, the solar glass, the ethylvinylacetate, the electricity and the PV panel factory. All materials except the PV panel factory are reduced for making a PERC panel.

There is a difference between the production of solar grade silicon and poly-silicon, which is caused by electricity usage. Producing poly-silicon requires more electricity, which drives up the impact of terrestrial eutrophication.

The results for terrestrial eutrophication are comparible to the results of marine eutrophication. The results of this study are 0.5 times the results of Müller, which in turn is more than half the value of PVPS2015 and Ecoinvent 3.7.



(a) Results per production step



(b) Comparison between studies

Figure 4.12: Results on terrestrial eutrophication

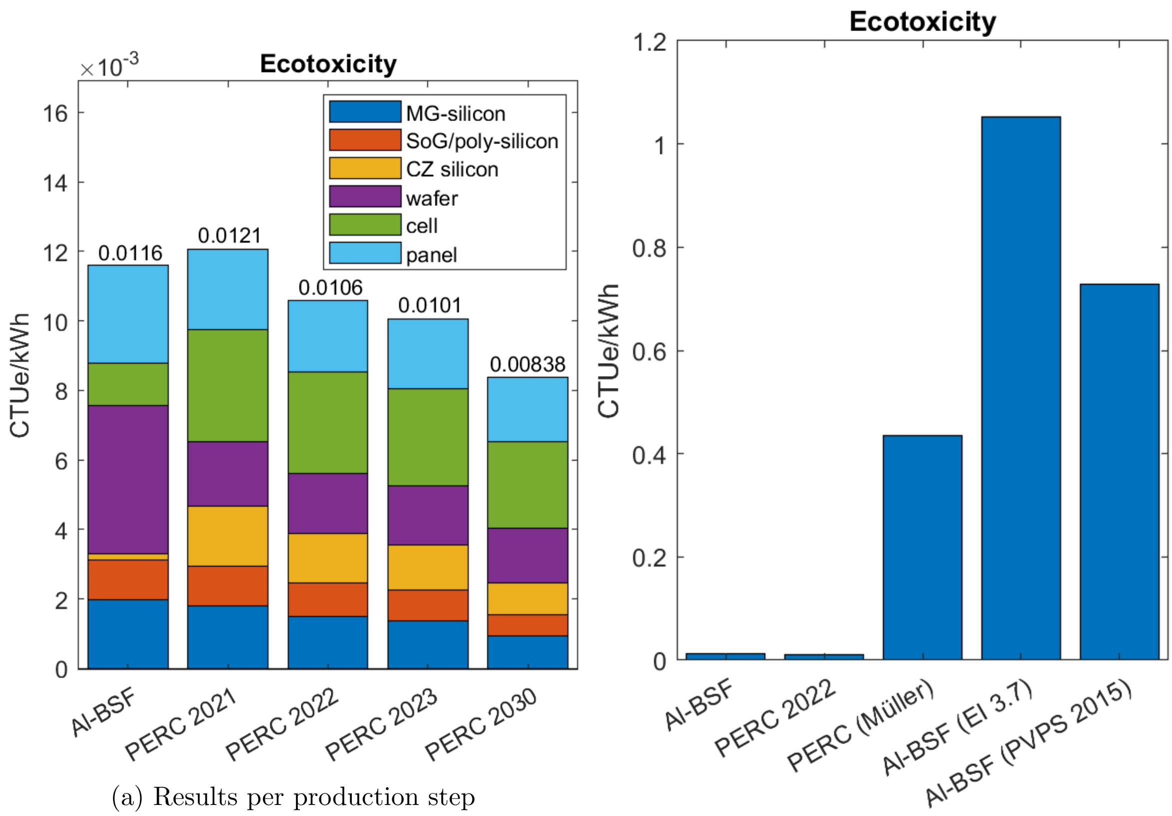
4.12 Ecotoxicity

There are big differences in three production steps: the Czochralski process, the production of the wafer, and the cell production. During the Czochralski process for PERC hydrocarbons are emitted into surface water, causing the most of the ecotoxicity in the production process. This emission is not present in the Al-BSF inventory, causing the difference in CZ silicon.

For producing a wafer with the Al-BSF inventory, deionised water has the largest share of ecotoxicity. The second largest is for dipropylene glycol monomethyl ether. Both these materials are not used in the PERC inventory, causing the large difference in ecotoxicity between the two types of cells.

The difference in cell production is the different type of water used. For Al-BSF tap water is used, and for PERC softened water. Softened water has a big impact on ecotoxicity, and results in an increase for the PERC cell production. Metallization paste also has a relative high impact on ecotoxicity, and is the biggest contributor for Al-BSF type cells.

The results of this study are very low compared to the other studies. The ecotoxicity for the PERC cell by Müller is 40 times higher than the PERC cell in this study.



(a) Results per production step

(b) Comparison between studies

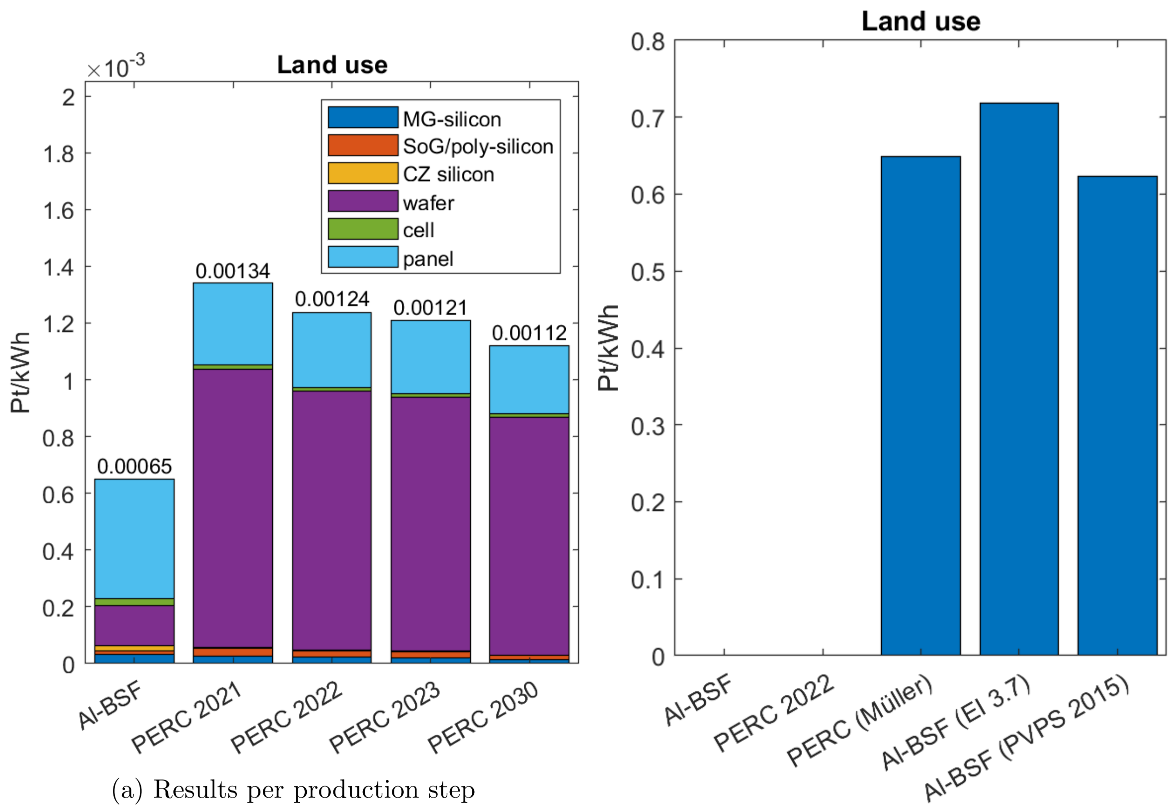
Figure 4.13: Results on ecotoxicity

4.13 Land use

The amount of land use has a large difference between the two types of wafers in the wafer production process. This can be attributed to citric acid, which is used in the PERC inventory but not in the Al-BSF inventory. The second material with high land use is water factory, which is the leading cause for Al-BSF.

The panel production causes high land use due to the use of alluminium alloy. This material has the biggest impact, and its reduction of use results in less land use for the PERC cell. Two other categories with high impact are solar glass, and PV panel factory. The solar glass is also reduced for PERC, and so the impact for panel production is reduced.

The results of this study are very low. By using IDEMAT for calculation, only the use of agricultural land an the tranformation from agricultural land is calculated. Land used for industrial purposes, infrastructure, contruction, and mineral extraction are not included in the calculation and result in zero land use. Transformation of land from forest, or to industrial, minderal extraction site, or traffice area is also not included. By not including all the land use and transformation, the results of this study are very low.



(a) Results per production step

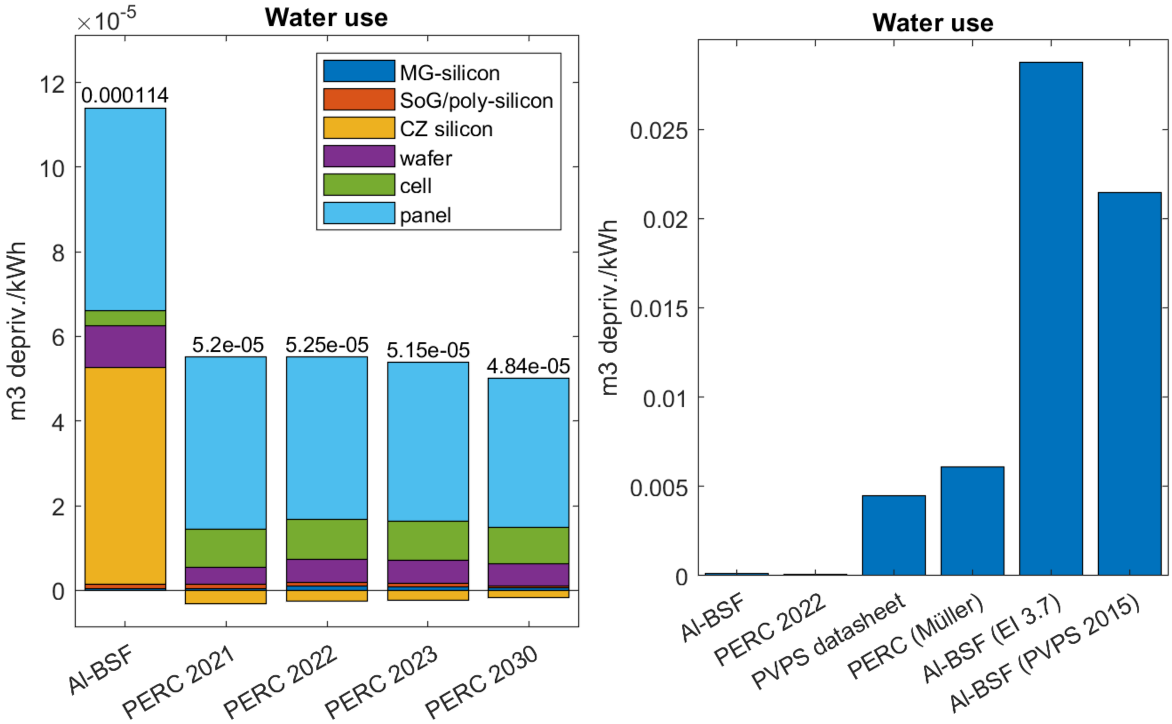
(b) Comparison between studies

Figure 4.14: Results on land use

4.14 Water use

The water use for panel production is not to direct water use, but is caused by the construction of the PV panel factory. The water use for the Czochralski process is used foor cooling, and flows back into nature. The amount of water at the output in the Al-BSF inventory is only 5% of the cooling water at the input. In the inventory for PERC, the water at input and output is almost equal, resulting in less impact on water use.

The water use is only calculated when the water is absorbed into the product, if the water flows back into nature, it will not be taken into account for this category. In this study, almost all water flows back into nature. In addition, tap water and deionised water from the IDEMAT inventory have zero water use, even though water is extracted from nature. Both these factors result in very low water use for this study compared tot the other studies.



(a) Results per production step

(b) Comparison between studies

Figure 4.15: Results on water use

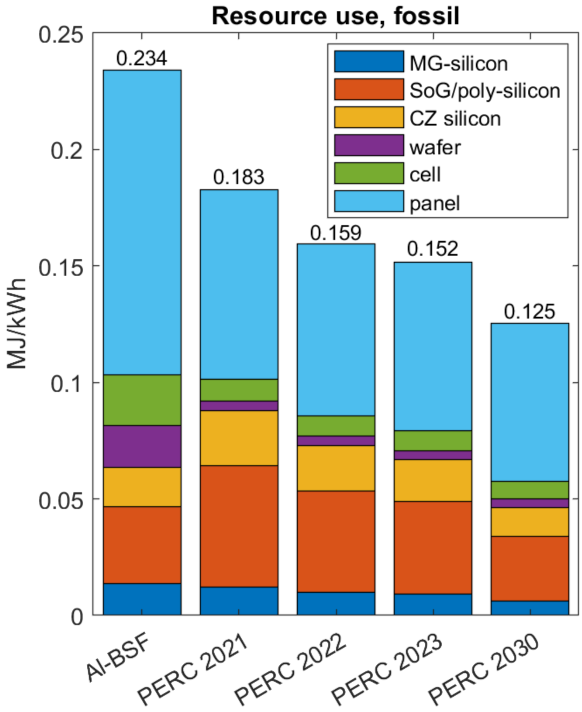
4.15 Resource use, fossil

The most fossil resource used is during the production of the panel. In this step, aluminium alloy has the largest share. Number two is the solar glass. The amount of aluminium and solar glass is reduced for creating a PERC panel, and so the resources used is reduced.

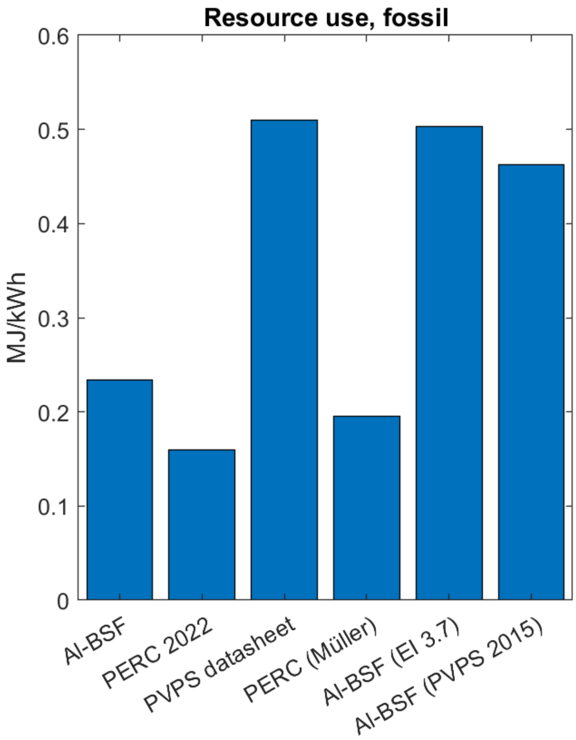
The second biggest impact on fossil resource used is the production of solar grade silicon and poly-silicon. In this production step, electricity and heat contribute the most to fossil resources used. Since poly-silicon uses more electricity and heat, the impact of poly-silicon on resource used is higher than for solar grade silicon.
For the Czochralski process, electricity has the highest fossil resource use. The PERC production uses less electricity in this step, but since more silicon is used per wafer, the impact of the silicon is higher. For the cell production, electricity is also the largest contributor.

The decrease in wafer the result of lowering the consumption of alkylbenzene sulfonate and electricity, and not using dipropylene glycol monomethyl ether in the PERC type cell.

Compared to the other studies, the results are comparable to the results from Müller. It is however twice as low as the results from the Al-BSF studies. This may be due to the fact that this study uses more up to dat einventory and an electricity mix with more renewable enrgy sources.



(a) Results per production step



(b) Comparison between studies

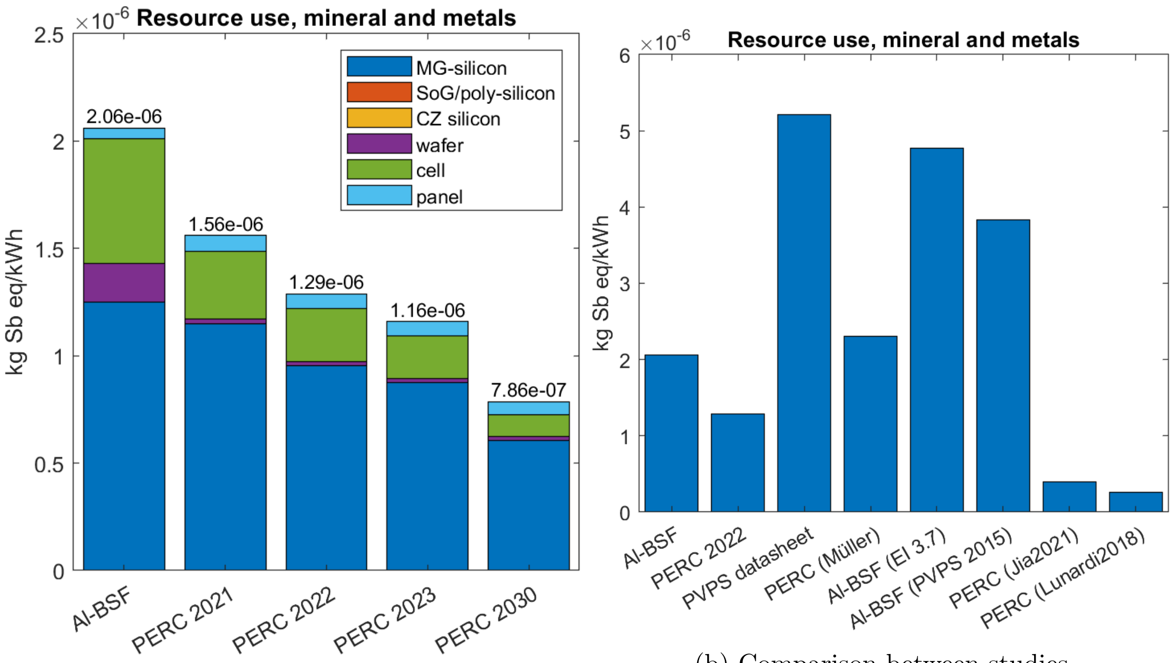
Figure 4.16: Results on resource use, fossil

4.16 Resource use, mineral and metals

The largest contributor is graphite, used in the production of metallurgical grade silicon. The same amount is used for every cell, but the amount of silicon used for Al-BSF is lower, hence a lower use of mineral and metals.

The decrease in mineral and metals use in cell production, is due to the lower amount of metallization paste used, which is the main contributor to this impact.

The studies done for Al-BSF type cells have high use of mineral & metals, while the PERC studies show lower values. The amount of resource use for this study is in between the other results.



(a) Results per production step

(b) Comparison between studies

Figure 4.17: Results on resource use, mineral & metals

4.17 Comparison to other energy sources

The result of this study is compared to other energy sources and the electricity mix of Europe. For wind energy a 2 MW onshore wind turbine from Gamesa is used, calculated with Simapro [67]. This wind turbine is manufactured in spain and then transported to the US. The nuclear power LCA is on two types of reactors in Switzerland. The pressurised water reactor (PWR) is chosen for the comparison, since the other type had limited available data. The difference between the two types of reactors is negligible compared to the other energy sources [68]. The study on hydro is done on an alpine region and a non-alpine region in Europe. Apart from climate change, the two regions have the same result and will be shown as one [69]. The electricity mix is taken from IDEMAT, and it consists of the electricity mix of Europe in 2019. For PV, the results of the 2022 PERC panel is chosen.

Figure 4.18 shows the amount of CO_2/kWh for different energy sources in logarithmic scale. For the renewable sources, wind had the highest amount of impact, and hydropower the lowest. When hydropower is used in mountainous area, it has an even lower impact. The PV panel has the second highest impact. All these renewable sources are considerably lower than the amount of impact the electricity mix has. More than 20 times the amount of CO_2 per kWh is emitted for the electricity mix than for 1 kWh generated by PV.

For particulate matter, nuclear power has the highest impact. This is caused by the improper tailing treatment of mining uranium. For wind energy, the majority of particulates are emitted during the welding process. Hydropower has the smallest impact on particulate formation. PV is in the middle compared to the renewable sources, and lower than the electricity mix.

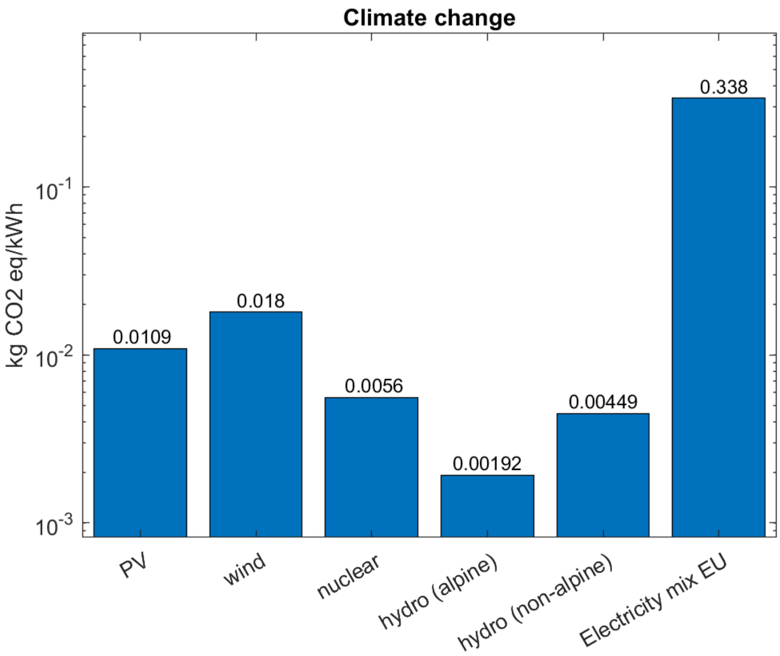
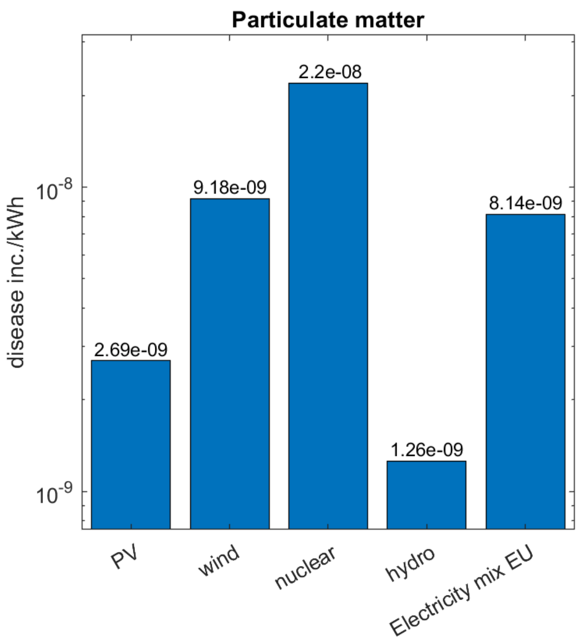
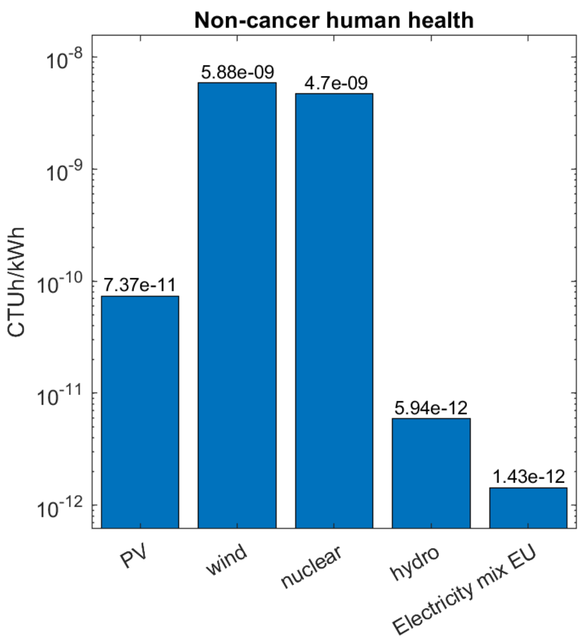


Figure 4.18: Comparison on climate change

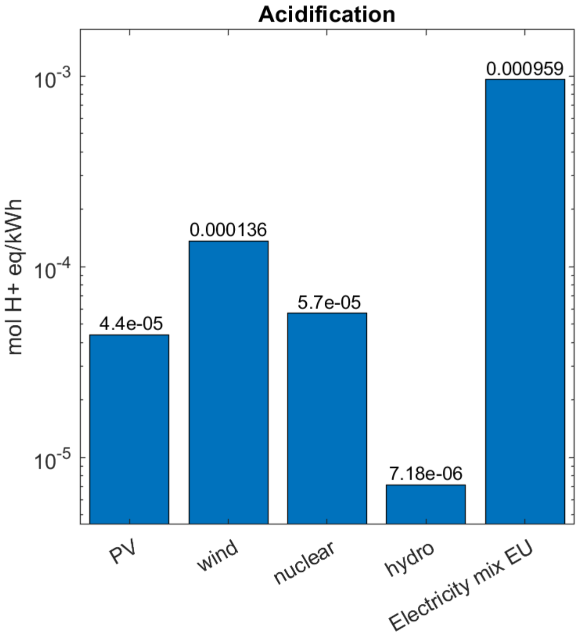


(a) Comparison on particulate matter

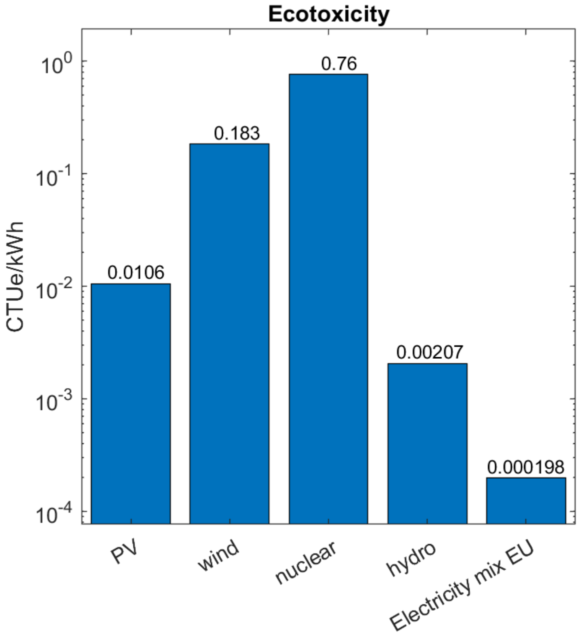


(b) Comparison on human health, non-cancer

The high value of non-cancer human health for nuclear power is attributed to the mining of uranium. For wind, the most impact is done in the raw material acquisition and manufacturing phase. The largest impact of human health at hydropower is the transportation of materials to the plant site. The amount of impact for the PV is lower than for wind and nuclear, but higher than hydropower and the EU electricity mix.



(a) Comparison on acidification



(b) Comparison on ecotoxicity

For acidificatoin, all renewable sources have a lower impact than the EU electicity mix. The lowest is hydropower, and the highest is the wind turbine. The wind turbine blades have to be covered in a sealant, which consists of materials with high acidification potential. The use of electricity generated from coal and gas contribute as well to the acidifcation in the manufacturing process. The amount of acidifcation for PV is around the same value of nuclear energy.

The biggest impact on ecotoxicity for nuclear power is the mining of uranium. This value differs per country, and can be brought down by excluding certain countries from mining. Wind power has the second highest impact on ecotoxicity, and PV takes the third place. For this category, the EU electricity mix has a very low value.

Looking at these five categories, it can be seen that hydropower has the lowest amount of impact combines. The impact from PV is consistently lower than wind power. For all categories excluding climate change, PV has also a lower impact on the environment than nuclear power.

The results are all presented in the midpoint category. With the use of Table 3.4 the endpoint categories are calculated. The total amount of damage to human health is 1.34E-08 DALY. The total damage to the ecosystem is 4.99E-11 species per year. The costs of the resources used is €3.20E-2.

Chapter 5

Conclusion and discussion

This study performed an LCA on two types of PV cells, the Al-BSF and the PERC type cells. The PERC cell was then adjusted to different years using current data and future trends.

The goal of this study was to compare the environmental impact of a PV panel to other studies on PV, and to other energy sources. A panel that is produced in Europe was examined, in the year 2022. For this study, a functional unit of 1 kWh was chosen. The system boundary included the phases from cradle-to-gate, so installation, maintenance, and End-of-Life was excluded.

For an M10 sized wafer, the following improvements have taken place or are expected to. The amount of poly-silicon per wafer is 17.5 g, 17 g, 16.5 g, and 13 g for 2021, 2022, 2023, and 2030 respectively. The kerf loss is 60 µm, 57 µm, 55 µm, and 45 µm for 2021, 2022, 2023, and 2030 respectively. The thickness of the wafer is 170 µm, 160 µm, 155 µm, and 140 µm for 2021, 2022, 2023, and 2030 respectively. The amount of silver per cell is 95 µg, 85 µ, 75 µg, and 55 µg for 2021, 2022, 2023, and 2030 respectively. The amount of aluminium is 1000 µg, 950 µg, 900 µg, and 790 µg for 2021, 2022, 2023, and 2030 respectively. The finger width is 33 µm, 30 µm, 27 µm, and 17 µm for 2021, 2022, 2023, and 2030 respectively. The most used inteconnection between cells changed from copper ribbons to copper wires, with a diameter of the wires of 305 µm, 295 µm, and 240 µm for 2022, 2023, and 2030 respectively.

The PERC module produced in 2022, has the following values of impact per category. Climate change 14.28 g CO_2/kWh; ozone depletion 1.675E-08 kg CFC11/kWh; ionising radiation 2.956E-05 kGq U-235/kWh; photochemical ozone formation 4.892E-05 kg NMVOC/kWh; particulate matter 4.021E-09 disease/kWh; non-cancer human health 1.093E-10 CTUh/kWh; cancer human health 3.716E-11 CTUh/kWh; acidification 5.64E-05 mol H^+/kWh; freshwater eutrophication 7.946E-07 kg P/kWh; marine eutrophication 6.629E-06 kg N/kWh; terrestrial eutrophication 6.972E-05 mol N/kWh; freshwater ecotoxicity 1.47E-02 CTUe/kWh; land use 1.36 pt/kWh; water use 5.61E-05 m^3/kWh; fossil resource use 0.213 MJ/kWh; mineral & metals resource use 2.569E-06 kg Sb/kWh.

For the categories climate change, acidification, marine eutrophication, terrestrial eutrophication, and fossil resource use, the aluminium and the solar glass have are the biggest contributor to the environmental impact.

The Al-BSF cell uses solar grade silicon, while PERC uses poly-silicon. The production of poly-silicon uses more electricity, which causes higher climate change, photochemical ozone formation, marine eutrophication, terrestrial eutrophication, and fossil resource use.

The production of metallurgical grade silicon has the highest share in impact for the categories ozone depletion, particulate matter, cancer human health, and mineral & metals resource use.

The difference between the Al-BSF and the PERC modules are due to a difference in material used, and a different amount of material used. When only the amount of the material is changed, the emissions are somewhat different. When other materials are used in the inventory, the difference in impact can be heavily influenced, and creates a larger difference results.

The Al-BSF cell uses less silicon per wafer than the PERC cell does, which causes the amount of environmental impact for the mettallurgical grade silicon, the solar grade silicon/poly-silicon and single crystalline silicon to increase for the PERC cell.

When comparing the results of the PV panel to other renewable energy sources, it can be seen that PV is lower than wind power and higher than hydro power in every impact category. PV is lower than nuclear power in particulate matter, non-cancer human health, and ecotoxicity, but higher in the category climate change. For acidification, PV and nuclear power are the same value. PV compared to electricity is lower in the categories climate change, particulate matter, and acidification. PV is higher for non-cancer human health and ecotoxicity.

5.1 discussion

For this study, only cradle-to-gate was analysed. This means that the transport to consumer, installation, maintenance, and end-of-life was not taken into account.

For transport in Europe, 200 km by truck and 500 km by train is assumed. When adding the environmental damage per kwh, the climate change and fossil resource use would increase by 0.06%. Marine and terrestrial eutrophication would increase by 0.04$ and acidification by 0.02%. The other categories have no increase in damage. With an impact so small, it can be neglected.

To include the installation, the balance of system has to be included into the calculations, defeating the purpose of calculation solely the solar panel. The results can differ per balance of system, which makes it more difficult to compare the different types of solar panels.

The maintenance of a solar panel is almost non existent and only consist of cleaning the panel. If the panel is tilted, rain is enough to clean the panels.

For the end of life of a PV panel, it can be recycled or end up in a landfill. One study says that recycling will have higher burden than benefits, since the process requires energy [20]. Another study says that the recycling will lower the impact on the environment [15]. Other studies have not implemented recycling due to lack of data, and it should be researched in future work [16][70][71].

The parameters used for the different type of cells are shown in table 3.1. The amount of polysilicon consumption for the PERC cell in 2021 is 17.5 g/wafer. Since this is an M6, the silicon consumption has gone up since the Al-BSF wafer. For the M6 cell to be between the amount of silicon per wafer for Al-BSF and the 2022 PERC, the silicon consumption would be around 15-16 g/wafer.

The input for the PERC cells are changed per year, but the emissions have stayed the same. The emissions used are based on ecoinvent, and are not for current production which means it might not be fully representative.

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Appendix

Table 1: Inventory of production of metallurgical grade silicon

	name	Coefficient	Unit	Source
Product	silicon, metallurgical grade	1.00E+00	kg	
Input	charcoal	1.70E-01	kg	Ecoinvent 3.8
	coke	2.31E+01	MJ	Ecoinvent 3.8
	electricity, medium voltage	1.10E+01	kWh	Ecoinvent 3.8
	graphite	1.00E-01	kg	Ecoinvent 3.8
	oxygen, liquid	2.00E-02	kg	Ecoinvent 3.8
	petroleum coke	5.00E-01	kg	Ecoinvent 3.8
	silica sand	2.70E+00	kg	Ecoinvent 3.8
	silicone factory	1.00E-11	unit	Ecoinvent 3.8
	wood chips, wet, measured as dry mass	5.50E-01	kg	Ecoinvent 3.8
Output	Aluminium	1.55E-06	kg	Ecoinvent 3.8
	Antimony	7.85E-09	kg	Ecoinvent 3.8
	Arsenic	9.42E-09	kg	Ecoinvent 3.8
	Boron	2.79E-07	kg	Ecoinvent 3.8
	Cadmium	3.14E-10	kg	Ecoinvent 3.8
	Calcium	7.75E-07	kg	Ecoinvent 3.8
	Carbon dioxide, fossil	3.58E+00	kg	Ecoinvent 3.8
	Carbon dioxide, non-fossil	1.61E+00	kg	Ecoinvent 3.8
	Carbon monoxide, fossil	1.38E-03	kg	Ecoinvent 3.8
	Carbon monoxide, non-fossil	6.20E-04	kg	Ecoinvent 3.8
	Chlorine	7.85E-08	kg	Ecoinvent 3.8
	Chromium	7.85E-09	kg	Ecoinvent 3.8
	Cyanide	6.87E-06	kg	Ecoinvent 3.8
	Fluorine	3.88E-08	kg	Ecoinvent 3.8
	Hydrogen fluoride	5.00E-04	kg	Ecoinvent 3.8
	Hydrogen sulfide	5.00E-04	kg	Ecoinvent 3.8
	Iron	3.88E-06	kg	Ecoinvent 3.8
	Lead	3.44E-07	kg	Ecoinvent 3.8
	Mercury	7.85E-09	kg	Ecoinvent 3.8
	Nitrogen oxides	9.74E-03	kg	Ecoinvent 3.8
	NMVOC	9.60E-05	kg	Ecoinvent 3.8
	Particulates, >10 um	7.75E-03	kg	Ecoinvent 3.8
	Potassium	6.20E-05	kg	Ecoinvent 3.8
	Silicon	7.51E-03	kg	Ecoinvent 3.8
	slag from metallurgical grade silicon production	2.50E-02	kg	Ecoinvent 3.8
	Sodium	7.75E-07	kg	Ecoinvent 3.8
	Sulfur dioxide	1.22E-02	kg	Ecoinvent 3.8
	Tin	7.85E-09	kg	Ecoinvent 3.8

Table 2: Inventory of production of poly-silicon

	name	Coefficient	Unit	Source
Product	silicon, poly-silicon	1.00E+00	kg	
Input	electricity, medium voltage	7.20E+01	kWh	Müller, 2021
	heat, district or industrial, natural gas	7.00E+01	MJ	Müller, 2021
	hydrochloric acid, without water, in 30% solution state	1.60E+00	kg	Ecoinvent 3.8
	hydrogen, liquid	5.01E-02	kg	Ecoinvent 3.8
	silicon, metallurgical grade	1.13E+00	kg	Müller, 2021
	silicone factory	1.00E-11	unit	Ecoinvent 3.8
	sodium hydroxide, without water, in 50% solution state	3.48E-01	kg	Ecoinvent 3.8
Output	AOX, Adsorbable Organic Halogen as Cl	1.26E-05	kg	Ecoinvent 3.8
	BOD5, Biological Oxygen Demand	2.05E-04	kg	Ecoinvent 3.8
	Chloride	3.60E-02	kg	Ecoinvent 3.8
	COD, Chemical Oxygen Demand	2.02E-03	kg	Ecoinvent 3.8
	Copper, ion	1.02E-07	kg	Ecoinvent 3.8
	DOC, Dissolved Organic Carbon	9.10E-04	kg	Ecoinvent 3.8
	Iron, ion	5.61E-06	kg	Ecoinvent 3.8
	Nitrogen	2.08E-04	kg	Ecoinvent 3.8
	Phosphate	2.80E-06	kg	Ecoinvent 3.8
	Sodium, ion	3.38E-02	kg	Ecoinvent 3.8
	TOC, Total Organic Carbon	9.10E-04	kg	Ecoinvent 3.8
	Zinc, ion	1.96E-06	kg	Ecoinvent 3.8

Table 3: Inventory of production of Czochralski process

	name	Coefficient	Unit	Source
Product	silicon, single crystal, Czochralski	1.00E+00	kg	
Input	argon, liquid	4.60E-02	kg	Müller, 2021
	ceramic tile	6.20E-02	kg	Müller, 2021
	electricity, medium voltage	3.84E+01	kWh	Müller, 2021
	hydrochloric acid, without water, in 30% solution state	4.38E-04	kg	Müller, 2021
	hydrogen fluoride	3.51E-03	kg	Müller, 2021
	lime, hydrated, packed	2.20E-02	kg	Müller, 2021
	nitric acid, without water, in 50% solution state	7.78E-03	kg	Müller, 2021
	silicon, poly-silicon	1.00E+00	kg	Ecoinvent 3.8
	silicone factory	5.00E-12	unit	Ecoinvent 3.8
	sodium hydroxide, without water, in 50% solution state	4.78E-03	kg	Müller, 2021
	water, completely softened	6.84E-02	kg	Müller, 2021
	Water, cooling, unspecified natural origin	2.33E+00	m3	Ecoinvent 3.8
Output	BOD5, Biological Oxygen Demand	1.30E-01	kg	Ecoinvent 3.8
	COD, Chemical Oxygen Demand	1.30E-01	kg	Ecoinvent 3.8
	DOC, Dissolved Organic Carbon	4.05E-02	kg	Ecoinvent 3.8
	Fluoride	2.37E-03	kg	Ecoinvent 3.8
	Hydrocarbons, unspecified	2.28E-02	kg	Ecoinvent 3.8
	Hydroxide	7.42E-03	kg	Ecoinvent 3.8
	Nitrogen	9.10E-03	kg	Ecoinvent 3.8
	TOC, Total Organic Carbon	4.05E-02	kg	Ecoinvent 3.8
	waste, from silicon wafer production, inorganic	1.00E-01	kg	Müller, 2021
	Water	3.00E-01	m3	Müller, 2021
	Water	2.20E+00	m3	Müller, 2021

Table 4: Inventory of production of the wafer

	name	Coefficient	Unit	Source
Product	single-Si wafer, photovoltaic	1.00E+00	m2	
Input	acrylic binder, without water, in 34% solution state	4.98E-03	kg	Müller
	alkylbenzene sulfonate, linear, petrochemical	3.40E-02	kg	Müller, 2021
	brass	7.45E-03	kg	Ecoinvent 3.8
	citric acid	1.87E-01	kg	Müller, 2021
	electricity, medium voltage	2.35E+00	kWh	Müller, 2021
	glass wool mat	1.06E-02	kg	Müller, 2021
	heat, district or industrial, natural gas	1.80E+00	MJ	Müller, 2021
	hydrogen peroxide, without water, in 50% solution state	2.53E-02	kg	Müller, 2021
	potassium hydroxide	3.81E-03	kg	Müller, 2021
	silicon, single crystal, Czochralski process, photovoltaics	6.91E-01	kg	This study
	sodium hydroxide, without water, in 50% solution state	1.50E-02	kg	Ecoinvent 3.8
	steel, low-alloyed, hot rolled	8.96E-04	kg	Müller, 2021
	wafer factory	2.00E-06	unit	Ecoinvent 3.8
	water, completely softened	2.17E+01	kg	Müller, 2021
	wire drawing, steel	8.96E-04	kg	Müller, 2021
Output	AOX, Adsorbable Organic Halogen as Cl	5.01E-04	kg	Ecoinvent 3.8
	BOD5, Biological Oxygen Demand	2.96E-02	kg	Ecoinvent 3.8
	COD, Chemical Oxygen Demand	2.96E-02	kg	Ecoinvent 3.8
	Copper, ion	6.05E-05	kg	Ecoinvent 3.8
	DOC, Dissolved Organic Carbon	1.11E-02	kg	Ecoinvent 3.8
	Nitrogen	9.94E-03	kg	Ecoinvent 3.8
	TOC, Total Organic Carbon	1.11E-02	kg	Ecoinvent 3.8
	waste, from silicon wafer production	2.00E-02	kg	Müller, 2021
	Water	9.75E-03	m3	Müller, 2021
	Water	2.50E-02	m3	Müller, 2021

Table 5: Inventory of production of the cell

	name	Coefficient	Unit	Source
Product	photovoltaic cell, single-Si wafer	1.00E+00	m2	
Input	ammonia, liquid	1.65E-02	kg	Müller, 2021
	calcium chloride	2.07E-01	kg	Müller, 2021
	electricity, medium voltage	6.03E+00	kWh	Müller, 2021
	heat, district or industrial, natural gas	3.55E+00	MJ	Müller, 2021
	hydrochloric acid, without water, in 30% solution state	6.81E-02	kg	Müller, 2021
	hydrogen fluoride	7.47E-02	kg	Müller, 2021
	hydrogen peroxide, without water, in 50% solution state	9.40E-02	kg	Müller, 2021
	metallization paste, back side	1.02E-03	kg	Müller, 2021
	metallization paste, back side, aluminium	9.01E-03	kg	Müller, 2021
	metallization paste, front side	3.16E-03	kg	This study
	nitric acid, without water, in 50% solution state	8.22E-02	kg	Müller, 2021
	nitrogen, liquid	2.62E+00	kg	Müller, 2021
	nitrous oxide	7.66E-03	kg	Müller, 2021
	oxygen, liquid	3.34E-01	kg	Müller, 2021
	phosphoryl chloride	1.82E-04	kg	Müller, 2021
	photovoltaic cell factory	4.00E-07	unit	Ecoinvent 3.8
	potassium hydroxide	1.51E-01	kg	Müller, 2021
	propane	4.14E-02	kg	Müller, 2021
	silicon tetrahydride	2.83E-03	kg	Müller, 2021
	single-Si wafer, photovoltaic	1.02E+00	m2	Müller, 2021
	solvent, organic	1.23E-02	kg	Müller, 2021
	sulfuric acid	2.06E-02	kg	Müller, 2021
	trimethylaluminium, solar grade	2.88E-04	kg	Müller, 2021
	water, completely softened	2.32E+01	kg	Müller, 2021
	Water, cooling, unspecified natural origin	2.31E-01	m3	Müller, 2021
	water, deionised	3.94E+01	kg	Müller, 2021
Output	Aluminium	7.72E-04	kg	Ecoinvent 3.8
	Ethane, hexafluoro-, HFC-116	1.19E-04	kg	Ecoinvent 3.8
	Hydrogen chloride	2.66E-04	kg	Ecoinvent 3.8
	Hydrogen fluoride	4.85E-06	kg	Ecoinvent 3.8
	Lead	3.48E-07	kg	Müller, 2021
	Methane, tetrafluoro-, R-14	2.48E-04	kg	Ecoinvent 3.8
	Nitrogen oxides	5.00E-05	kg	Ecoinvent 3.8
	NMVOC, non-methane volatile organic compounds	1.94E-01	kg	Ecoinvent 3.8
	Particulates, <2.5 um	2.66E-03	kg	Ecoinvent 3.8
	Silicon	7.27E-05	kg	Ecoinvent 3.8
	waste, from silicon wafer production, inorganic	6.41E-03	kg	Müller, 2021
	wastewater from PV cell production	1.32E-02	m3	Müller, 2021
	Water	1.68E-02	m3	Müller, 2021
	Water	2.77E-01	m3	Müller, 2021

Table 6: Inventory of production of the panel

	name	Coefficient	Unit	Source
Product	photovoltaic panel, single-Si wafer, glass-backsheet	1.00E+00	m2	
Input	1-propanol	1.72E-02	kg	Müller, 2021
	adipic acid	3.69E-04	kg	Müller, 2021
	aluminium alloy, AlMg3	1.51E+00	kg	Müller, 2021
	copper	1.48E-01	kg	Müller, 2021
	Corrugated board box	7.63E-01	kg	Ecoinvent 3.8
	diode, auxilliaries and energy use	2.81E-03	kg	PVPS, 2015
	electricity, medium voltage	3.32E+00	kWh	Müller, 2021
	ethylvinylacetate, foil	7.93E-01	kg	Müller, 2021
	EUR-flat pallet	0.05	unit	Ecoinvent 3.8
	Extrusion, plastic film	3.36E-01	kg	Müller, 2021
	glass fibre reinforced plastic, polyamide, injection moulded	1.88E-01	kg	Ecoinvent 3.8
	lead	1.08E-02	kg	Müller, 2021
	lubricating oil	1.61E-03	kg	Ecoinvent 3.8
	Packaging film, low density polyethylene	4.01E-02	kg	Ecoinvent 3.8
	photovoltaic cell, single-Si wafer	8.98E-01	m2	Müller, 2021
	photovoltaic panel factory	4.00E-06	unit	Ecoinvent 3.8
	polyethylene terephthalate, granulate, amorphous	2.81E-01	kg	Müller, 2021
	polyethylene, high density, granulate	2.42E-02	kg	Müller, 2021
	Polyethylene, low density, granulate	5.48E-02	kg	Müller, 2021
	polyvinylfluoride, film	4.51E-02	kg	Müller, 2021
	silicone product	1.44E-01	kg	Müller, 2021
	solar glass, low-iron	8.00E+00	kg	Müller, 2021
	tempering, flat glass	8.00E+00	kg	Müller, 2021
	tin	1.04E-02	kg	Müller, 2021
	Water, cooling, unspecified natural origin	7.16E-02	m3	Müller, 2021
	wire drawing, copper	1.48E-01	kg	Müller, 2021
Output	Carbon dioxide, fossil	2.18E-02	kg	PVPS, 2015
	Heat, waste	1.34E+01	MJ	PVPS, 2015
	municipal solid waste	9.69E-02	kg	Müller, 2021
	NMVOC	8.06E-03	kg	PVPS, 2015
	waste mineral oil	1.61E-03	kg	Ecoinvent 3.8
	waste plastic, mixture	2.48E-02	kg	Müller, 2021
	waste polyvinylfluoride	9.02E-04	kg	Müller, 2021
	Water	2.79E-02	m3	Müller, 2021