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The Social and Environmental Sustainability in Photovoltaic Module Supply Chains

Sosial og Miljømessig Bærekraft i Leveransekjeden til Fotovoltaiske Moduler

Bachelor's thesis in Renewable Energy
Supervisor: Simon B. B. Solberg
May 2023

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Preface

This bachelor thesis was written as a collaborative effort between three students from the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. The thesis is worth 20 ECTS as the last subject of the study program Bachelor in Engineering, Renewable Energy. This marks the end of the three year bachelor program.

The aim of this study was to gain insight into the global solar industry from raw mineral extraction to module manufacture. Through choosing three different modules and mapping their supply chains, it was possible to create an oversight over the current PV production chain market and its level of sustainability. This was done through research compiling secondary source material as well as conducting a life cycle assessment through the program Simapro to compare the chosen modules.

This research and life cycle assessment was done on behalf of Aneo. The finished thesis aims to aid the company in their navigation of the PV module market. In addition to the results regarding the three chosen modules, the methodology used to assess social and environmental sustainability may assist Aneo in their work in the future.

In closing, the group wants to express its appreciation for the help and support received during the process of creating this thesis. Firstly, we would like to thank our NTNU supervisor Simon B. B. Solberg, for the help, shared experience and positivity. Secondly, we would like to thank our Aneo supervisors, Martin Gjertsen and Bjørn Thorud, for valuable insight into the industry and guidance. We also want to extend our gratitude to Nariê Rinke Dias de Souza for her LCA guidance and reassurance. Lastly, we would like to express our gratitude towards friends and family for motivation and inspiration.

Trondheim, 22nd of May 2023

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Abstract

The need for renewable energy is rapidly increasing, and solar energy is emerging as the fastest growing energy industry in the world. China has the majority market share for the whole supply chain for photovoltaic (PV) modules, from quartz extraction to finished panels. As the industry grows, the impact from the production of PV modules have garnered increasing international attention, because of both the integrated emissions from production, and the discovered use of forced labour in large parts of the production of PV modules.

Xinjiang is a province in China with a substantial silicon refining industry. Therefore, a large part of China's solar energy production originates from, or is connected to Xinjiang in some way. For several years, the local government and industry has faced accusations of the use of forced labour in several of their production sites. When the report *In Broad Daylight*, which focuses on forced labour in the PV industry, was released in 2021, several actors on the market started the work of avoiding products with ties to Xinjiang.

To assess the social and environmental sustainability, modules from the three companies, JA Solar, Risen Energy and Hanwha Qcells, was chosen to examine supply chains and emissions. JA Solar and Risen Energy are both major Chinese cell and module manufacturers with a significant market share. The South Korean company, Hanwha Qcells has a smaller production than JA and Risen, but is still among the top producers of PV modules in the world. Whilst JA and Risen have most of their supply chain and production located in China, Qcells is more dispersed with plants in the US as well as China and the Asia-Pacific region.

The calculations of emissions was done through a life cycle assessment (LCA) performed with the program Simapro. The LCA was based on a life cycle inventory (LCI) provided by the International Energy Agency (IEA), with alterations made to make LCIs suited to the three companies. The calculations showed an emission level of 667, 618 and 418 kg CO_2-eq/kWp for JA Solar, Risen Energy and Hanwha Qcells respectively. Out of this, the electricity used in the process stages represented 402, 426 and 155 kg CO_2-eq. This shows that by using hydro power in the polysilicon production, Qcells reduced its emissions by approximately a third.

Through literary studies, it was shown that JA and Risen had similar exposure to forced labour, particularly through their supplier deals with Xinte, GCl-Poly and Hoshine. Risen has however plans to establish autonomy over parts of their supply chain, which will reduce their exposure in the future whilst JA has not announced any similar plans. The least exposed company is Hanwha Qcells, which is only exposed through a possible connection to Hoshine.

The solar energy market is constantly developing and adapting to new challenges. In response to the accusation of forced labour in PV related industry in Xinjiang, new policies and regulations has emerged to combat this. The US has implemented a ban on all products with ties to Xinjiang, and the EU has a pending ban proposal in the European Parliament. Regarding the increasing focus on lowering integrated carbon emissions, both France and South Korea has implemented carbon footprint certification to support the companies with less production related emissions. These new policies will likely shape the future of the PV market. As such, looking to these regulations as guidelines for choosing sustainable modules may aid companies like Aneo in navigating the future PV market.

Sammendrag

Behovet for fornybar energi øker raskt, og solenergi er i ferd med å bli den raskest voksende energibransjen i verden. Kina har majoritetsmarkedsandel for hele forsyningskjeden for solcelle paneler, fra utvinning av kvarts til ferdige paneler. Ettersom bransjen vokser, har påvirkningen fra produksjonen av solcellepaneler fått økende internasjonal oppmerksomhet, på grunn av både de integrerte utslippene fra produksjonen og den mistenkte bruken av tvangsarbeid i store deler av solcelleprodukjonen.

Xinjiang er en provins i Kina med betydelig produksjon av polysilisium. Derfor stammer en stor del av Kinas solcelleproduksjon fra, eller er tilknyttet Xinjiang. I flere år har den lokale regjeringen og industrien blitt anklaget for bruk av tvangsarbeid på flere av produksjonsstedene. Da rapporten "In Broad Daylight" som omhandler bruken av tvangsarbeid i solcelleindustrien, ble utgitt i 2021, begynte flere aktører på markedet å arbeide for å unngå produkter med tilknytning til Xinjiang.

Moduler fra de tre selskapene JA Solar, Risen Energy og Hanwha Qcells ble valgt for å vurdere sosial og miljømessig bærekraft, gjennom å undersøke forsyningskjeder og utslipp. JA Solar og Risen Energy er begge store kinesiske produsenter av solcellepaneler med betydelig markedsandel. Det sørkoreanske selskapet Hanwha Qcells har mindre produksjon enn JA og Risen, men er likevel blant de største produsentene av solcellepaneler i verden. Mens JA og Risen har mesteparten av sin forsyningskjede og produksjon i Kina, er Qcells mer spredt med fabrikker i USA, samt Kina og Asia-Stillehavsregionen.

Utslippsberegningene ble gjort gjennom en livssyklusanalyse (LCA) utført med programvaren Simapro. LCA-en var basert på en livssyklusinventar (LCI) levert av International Energy Agency (IEA), med endringer gjort for å tilpasse LCI-ene til de tre selskapene. Beregningene viste et utslippsnivå på henholdsvis 667, 618 og 418 kg CO_2-eq/kWp for JA Solar, Risen Energy og Hanwha Qcells. Av dette representerte elektrisiteten brukt i prosessene 402, 426 og 155 kg CO_2-eq. Dette tyder på at å bruke vannkraft i produksjonen av polysilisium, reduserte utslippet til Qcells med omtrent en tredjedel.

Gjennom litteraturstudier ble det vist at JA og Risen hadde lignende eksponering for tvangsarbeid, spesielt gjennom avtaler med leverandørene Xinte, GCl-Poly og Hoshine. Risen har imidlertid planer om å oppnå autonomi over deler av sin forsyningskjede, noe som vil redusere deres eksponering i fremtiden, mens JA ikke har kunngjort noen lignende planer. Det minst eksponerte selskapet er Hanwha Qcells, som bare er eksponert gjennom en mulig forbindelse til Hoshine.

Solenergimarkedet utvikler seg kontinuerlig og tilpasser seg nye utfordringer. Som respons på anklagene om tvangsarbeid i solcelle relatert industri i Xinjiang har det oppstått ny lovgiving for å bekjempe dette. USA har innført et forbud mot alle produkter med tilknytning til Xinjiang, og EU har et fremmet et lignende lovforslag i Europaparliamentet. Når det gjelder det økte fokuset på å redusere integrerte karbonutslipp, har både Frankrike og Sør-Korea innført karbonfotavtrykk-sertifisering for å støtte selskaper med mindre produksjonsrelaterte utslipp. Disse nye tiltakene vil sannsynligvis forme fremtiden for solindustrien. Derfor kan det være gunstig for selskaper som Aneo å se på disse reguleringene som retningslinjer for å velge bærekraftige moduler, samt å navigere i fremtidens solcellemarked.

Contents

List of Terms and Abbreviations

CO_2	Carbon dioxide
CFP	Carbon footprint
CSR	Corporate social responsibility
EVA	Ethyl vinyl acetate
GW	Giga watt
HJT	Hetero-junction
IEA	The International Energy Agency
kWh	Kilo watt hour
kWp	Kilo watt peak
LCA	Life cycle assessment
LCI	Life cycle inventory
LCOE	Levelised cost of electricity
MG-Si	Metallurgical grade silicon
PV	Photovoltaic
SoG-Si	Solar grade silicon
TWh	Terra watt hour

List of Figures

List of Tables

1 Introduction

Europe is currently facing an energy crisis. This shortage of energy is a complex situation, caused by the Russian invasion of Ukraine, a transition from fossil fuels to renewable energy and recent unpredictable weather, causing poor wind and hydro power production. The need to meet the current demand for power has led to several countries increasing their plans for solar power installations. Solar energy is currently the fastest growing energy industry in the world, largely due to it being inexpensive and easy to install. For the European Union, the production of solar energy has become an important factor for decreasing their dependence on Russian oil and gas [1]. China is currently responsible for a majority of the worlds solar energy manufacturing. However the labour conditions and integrated emissions during production has recently garnered international attention.

The production in China is driven and accelerated by government sponsored subsidies and tax reliefs [2]. Simultaneously with the Chinese expansion of the PV industry, the Chinese government implemented labour transfer programs and labour camps specifically targeted towards Uyghurs. The Uyghur people are an ethnic minority in China with Muslim heritage. The labour transfer programs and camps have several times been accused of being a front for forced labour. According to a report published in 2021 called *In Broad Daylight*, a substantial part of the global solar supply chain was indirectly implicated in the use of forced labour through these camps [3].

China has become a leading industrial nation, partly through the use of coal and fossil based power plants to fuel production [2]. A consequence of this is that much of the worlds “clean” solar energy has hidden emissions that is not necessarily considered when evaluating different power sources. As the the world transitions towards more sustainable energy sources, the actual integrated emissions and subsequent social conditions during production will likely become increasingly more important.

Figure 1.1: UN's sustainable development goals 7, 8 and 10 [4].

The United Nations sustainable development goals define several goals applicable to the current situation in the solar energy industry. In the case of unethical working conditions in the solar industry, striving to achieve goal 7 of “Affordable and clean energy” is not compatible with goals 8 and 10, describing “Decent work” and “Reduced inequalities” [5]. These three development goals are presented in Figure 1.1. To continue expanding the worlds solar capacity without counteracting goal 8 and 10, countries has taken different approaches. The US has implemented bans on all goods from Xinjiang without proof of a forced labour free production [6], while France and Korea has implemented rules and regulations to favour the more environmentally sustainable solar panels [7, 8]. How the world continues to react to the production situation in China will likely be critical for the development of the industry.

1.1 Aneo

With the social and environmental challenges facing the solar industry today, navigating the industry can be challenging. As a tool to maneuvre the industry, this thesis was requested by the renewable energy company, Aneo. Aneo is a Norwegian company working with renewable energy production, energy efficiency and electrification. The company is the result of a cooperation between the companies TrønderEnergi and HitecVision and is divided into six different departments; mobility, retail, build, industry, energy management and real estate. This thesis is written specifically in cooperation with Aneo Real Estate, the department in Aneo focusing on solar installations on commercial buildings.

Aneo is aiming to have installed solar power plants producing 1 TWh within 2030[9], therefore it is important for to have a thorough insight into the modules they will be using. To avoid modules produced in an unethical or polluting manner, it is necessary to examine the current market and the supply chains to the modules being used today, in addition to the future market as to examine future module possibilities. This bachelors thesis will therefore focus on the supply chain of three of the biggest solar module manufacturers on the market today, the tier 1 manufacturers JA Solar, Risen Energy and Hanwha Qcells. Out of these three, only JA Solar's modules have been used in Aneo's installations.

To best meet Aneo's needs, this thesis will attempt to analyse the supply chain and the material origins of the chosen modules. This will be done through performing a life cycle assessment on the three solar modules. The thesis also aims to analyse the potential use of forced labour in the supply chain of the modules. This will be done to establish both the social and environmental contributions of the solar modules. Additionally, the thesis will present the current political and economical standings of EU and the US in regards to the PV industry, to give a prediction as to how the market will evolve in the coming decade. As a conclusion, this thesis will attempt to give a thorough breakdown of the solar energy production chain, and present the information necessary for Aneo to make an informed decision about different modules on the market.

2 Photovoltaics

The sun is a vast energy source. The amount of photons hitting the earths surface in one and a half hours carries enough energy to theoretically cover the planets energy demand for a whole year. Solar panels, also known as photovoltaic (PV) modules, are devices that directly convert sunlight into electricity. The PV module absorbs the energy from the sunlight, transforming it into electrical potential [10].

Solar energy is the fastest growing energy source in the world. In 2010 PV installations produced 30 TWh of energy. Since then the technology and production has rapidly increased. In 2021, PV installations produced a total of 1002.9 TWh of energy, accounting for 3.6% of the global electricity production. This was a 22% increase from 2020. Solar energy is also becoming the energy source with the lowest levelised cost of electricity (LCOE). This combined with the global goal to reach net zero emissions by 2050 is expected to accelerate the investment in the coming years. The projections of the International Energy Agency (IEA) estimates that by 2030 solar energy production will increase to 7000 TWh, seven times higher than 2021 [11, 12].

Today's PV market consists mainly of three different types of modules, divided into three different generations. The third generation of PV is a collection of PV technologies aiming to increase efficiency past the traditional limit of 41%. The new technologies has potential to reach efficiency levels of up to 60%. The new modules employs multiple layers within the cells that absorbs different parts of the radiation spectrum, making it possible to reach such high efficiency levels. Despite the high efficiency, the cost of production has led third generation PV to not yet making it past prototyping [13, 14].

Second generation is called thin film PV. These technologies have a lower efficiency of around 5-15%, but also a low material cost. The advantage of thin film is its flexible use. As the PV material is bendable and light weight, it can be used in various different applications. Thin film PV has been around since the 1970s, but still only represent a small percentage of the total PV production [13, 14].

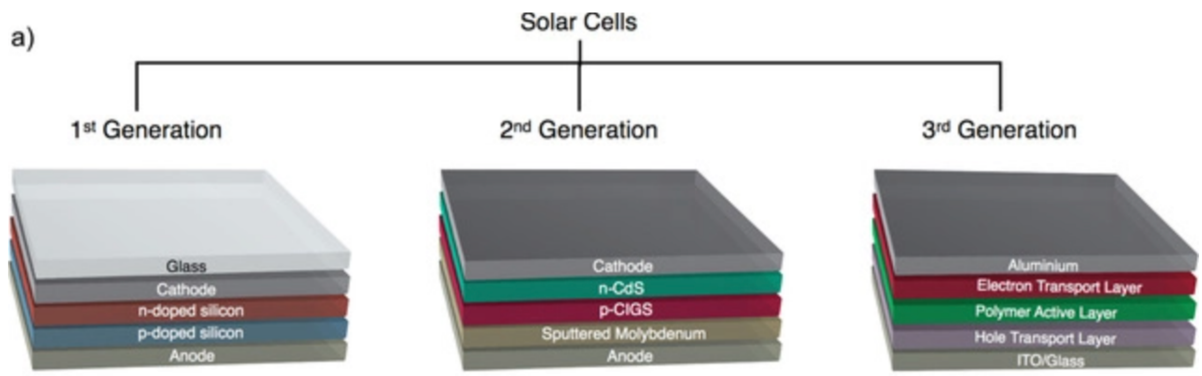


Figure 2.1: The three generations of PV modules [14].

The first generation of PV is the most common technology utilised today. These modules generally produce efficiency levels of around 16-22%. The modules are comprised of several cells made of crystalline silicon wafers, connected by conductor material and placed inside a framed casing. To produce electricity, the cells contain what is called a p-n junction, which is created through a process called "doping". One side of the junction is p-doped, meaning the silicon wafer is infused with an element containing only three valence electron in the outer electron shell. This process creates electron holes in the doped silicon and is usually done with elements like Boron or Gallium. The other side is n-doped with an element containing five valence electrons, creating a doped silicon with excess electrons. The most common n-doping element is Phosphorus. Where the two sides meets, the excess electrons fill the available electron holes. This in turn creates a positive and negative field, a voltage barrier, over which no more electrons can cross. When the sun hits the p-n junction it frees an electron from the p-doped silicon, simultaneously creating an electron hole. The electric field pushes the electron to the n-doped side and the available spot to the p-doped side, however they cannot cross the voltage barrier. It is then possible to connect an electric load between the to sides, causing electrons to flow to the other side through the load, creating an electric current [13, 14].

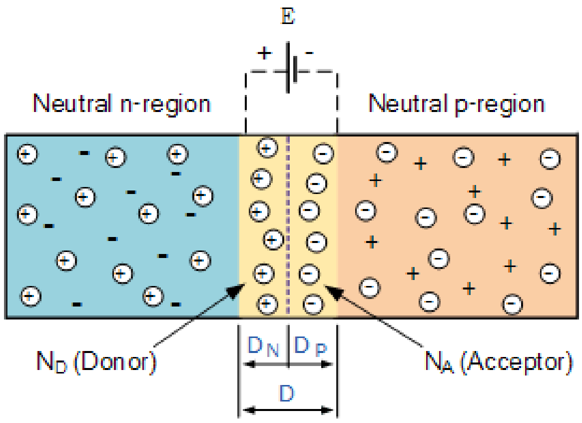


Figure 2.2: An illustration of the p-n junction, the electric field created by combining p-doped silicon and n-doped silicon [15].

Half-cut solar cells is a new technology included in first generation of PV modules, and is today used by most PV manufacturers. As the name implies, the cells in the module is cut in half. Usually modules have 72 cells connected in three different series. Half-cell modules has twice as many cells and series. This causes less current to go through the cells, resulting in less heat loss and strain on the cells. Another advantage is the number of series in the module. When a cell is shaded, the rest of the series will stop producing electricity. In traditional modules a single shaded cell will cut one third of the electricity production. Comparatively, a half-cut module only loses one sixth of the production. Therefore half-cut modules outperform regular PV modules in both efficiency and life expectancy [16].

3 Chain of production

The process of producing photovoltaic modules, from extraction of raw materials to the manufacturing of the finished product, is generally considered as consisting of seven steps. The process begins with the extraction of quartz, continues with purification and reshaping of the silicon and culminates in the assembly of the module with its related components. Although there are some variations in production, most companies tend to utilise the same processes in PV production.

3.1 Raw materials

The first step in the PV supply chain is the extraction of silicon from raw materials. The raw materials in question is either quartzite extracted from mines or quartz sand [17, 18]. Quartzite consists of sandstone incorporated with quartz crystals [19]. Silicon is the second most abundant periodic element in the earths crust after oxygen, making the occurrence of quartz with a chemical composition of SiO_2 rather common.

3.2 Metallurgical grade silicon

In a process utilising high temperature furnaces and carbon, the oxygen and silicon in the quartz is separated. The carbon used is a mixture of coal, coke and wood chips. Being exposed to a temperature of over 2000 K, the carbon binds the oxygen, leaving the purified silicon to be extracted as a liquid from the bottom of the furnace. This process is illustrated in Figure 3.1. When the silicon extracted from the raw materials have a purity level around 98 %, meaning the substance contains about 98 % silicon atoms, it is classified as metallurgical grade silicon (MG-Si). The MG-Si is then solidified and prepared for the next process, transforming into polycrystalline silicon [20].

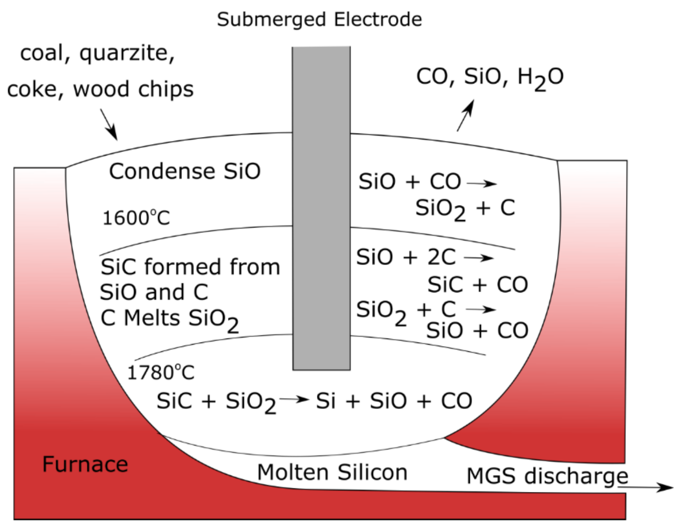


Figure 3.1: A concept drawing of a MG-Si furnace [21].

The majority of the worlds MG-Si is used in aluminium alloys and silicones. The remainder is then mainly used for high purity polycrystalline silicon applied in the semiconductor and PV industries [22]. As the PV industry is steadily growing, the fraction used for PV panel production is expected to increase in the next decades.

3.3 Polycrystalline silicon

The next stage in the production chain is another purification process, where MG-Si is transformed into polycrystalline silicon, also referred to as polysilicon. Polysilicon is defined by a higher purity than MG-Si. The level of purity depends on the intended use. When the silicon reaches a minimum purity level called 6N or six nines, meaning the silicon is 99.9999 % pure, it can be classified as solar grade silicon (SoG-Si) [20]. The step of refining of MG-Si to polysilicon in the manufacturing can be performed with several different technologies. Of which, the two most common technologies are presented in Figure 3.2.

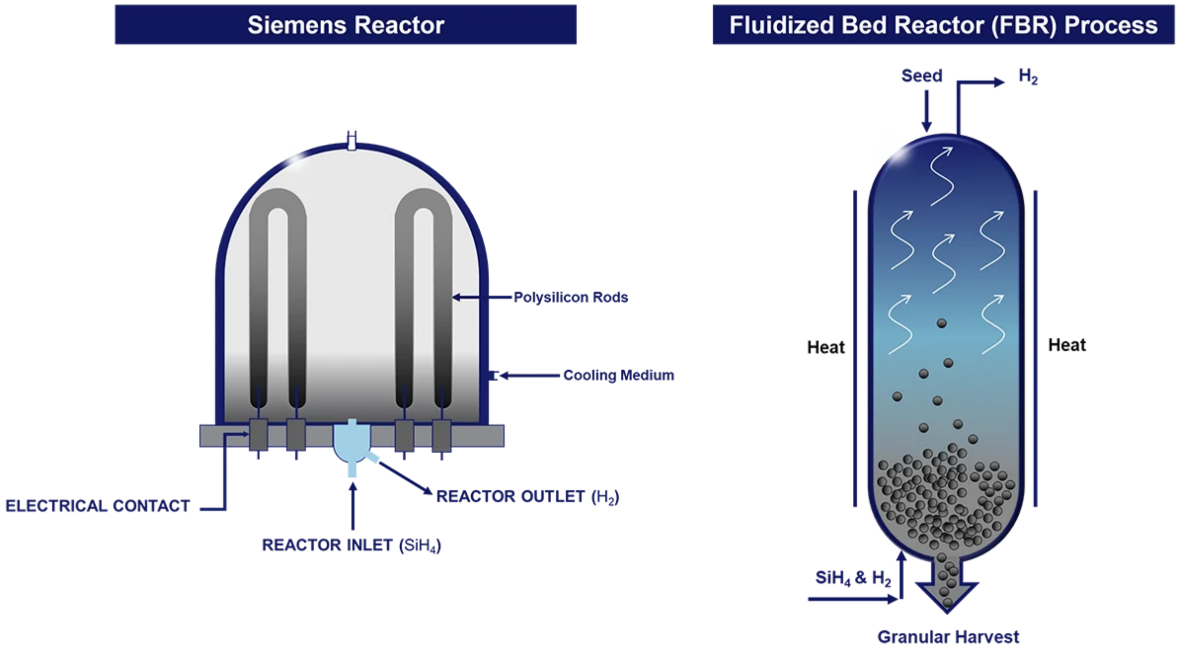


Figure 3.2: Two methods of polysilicon production, the Siemens process and the FBR [23].

3.3.1 The Siemens Process

The most widely used technology to refine MG-Si to polysilicon is the Siemens process. Polysilicon is vaporised and reacts with hydrochloric acid at high temperatures, resulting in a gas mixture. This gas is introduced to the Siemens reactor, where the temperature is raised until the silicon and hydrogen separate. The separated, and now purified silicon will then deposit on rods in the reactor made of high-purity polysilicon. The rods subsequently grow in size, and when the rods reach the preferred size of 15 to 20 cm in diameter, the process is finished. The rods are usually broken into chunks before further processing [22, 20].

3.3.2 Fluidized Bed Reactors

While less energy intensive than the Siemens process, the fluidized bed reactor (FBR) silicon refining process is significantly less used in the PV industry. The FBR process requires just 10% of the electricity required by the Siemens process [24, 23]. However, other complications has lead to the limited use of FBR technology in the industry. The amount of unusable silicon waste in the process is one reason. Another is the required time, experience and financial investment to expand a FBR system from lab scale to industry scale [24].

An FBR vaporises the silicon, which then reacts with hydrogen to create silane gas. This gas is then introduced to the fluidized bed reactor. The reactor contains "seed granules", which is small particles of purified silicon. In the reactor, the silane gas is separated into silicon and hydrogen gas. The silicon will bond with the granules, depositing themselves as purified silicon while the hydrogen gas is extracted from the reactor. The granules will grow in size until sufficiently large, drop to the bottom of the reactor and then be removed as the finished product. This process, unlike the Siemens process, can continuously produce polysilicon without having to stop to extract the product [24]. Both the FBR and the Siemens technologies are presented in Figure 3.2.

3.3.3 Recycling of polysilicon kerf

During the production stage where polysilicon ingots are cut into wafers, approximately 40% of the polysilicon is lost in the process. This lost polysilicon is called kerf. The kerf consists of the silicon left after cutting the wafers, mixed with a solution used in the cutting process. This solution has to be separated from the silicon particles and then reshaped into usable sized pieces of polysilicon [25]. Through his method, the kerf is recycled into usable polysilicon that can again be molded into ingots, thereby theoretically reducing the need for new polysilicon with upwards of 40% [25].

Even though this recycling technology exists, it is not yet common in the industry. The reorganisation and construction of the polysilicon plants to equip them to recycle kerf requires major financial investments. According to a representative from REC Solar, R. Almaas, this is a major reason as to why kerf recycling is not a widely used technology.

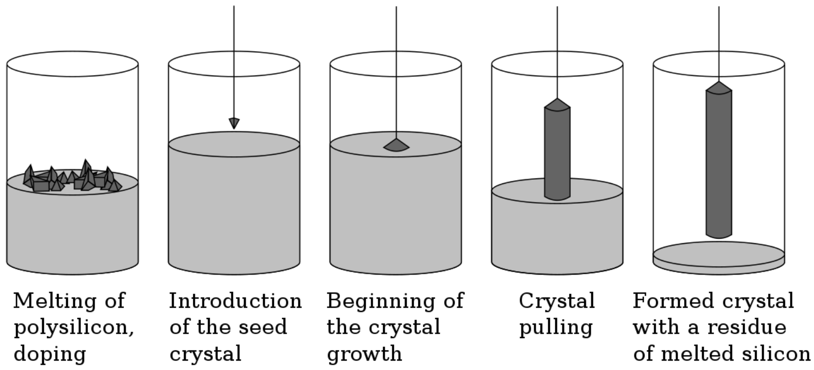
3.4 Ingots

To improve the efficiency of the solar module, monocrystalline silicon is preferred to polycrystalline [26]. To make a monocrystalline PV module, the polysilicon produced in the previous processes has to be altered as to become one single crystal, as well as shaped into an ingot to be used further in the chain of production. To produce this monocrystalline ingot, two processes are commonly utilised, the Czochralski method and the Float Zone (FZ) method. It is commonly during these processes that the silicon is p-doped [27, 28].

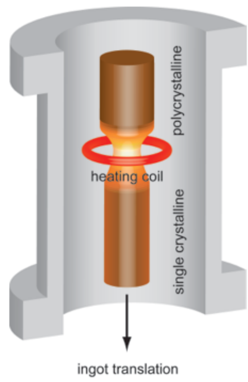
3.4.1 The Czochralski method

In the Czochralski method, a seed crystal is dipped into a pot of melted polysilicon, in an isolated chamber. The crystal will then be rotated while pulled upwards at a speed where the polysilicon has time to crystallise on the seed crystal. The speed of the pulling determines the diameter of the resulting ingot. The crystal ingot will then be pulled upwards until a single crystal of wanted diameter and length has been formed [27, 29, 30].

Figure 3.3: Ingot processing



(a) A step-by-step illustration of the Czochralski method [31].



(b) An illustration of the Float Zone method [32].

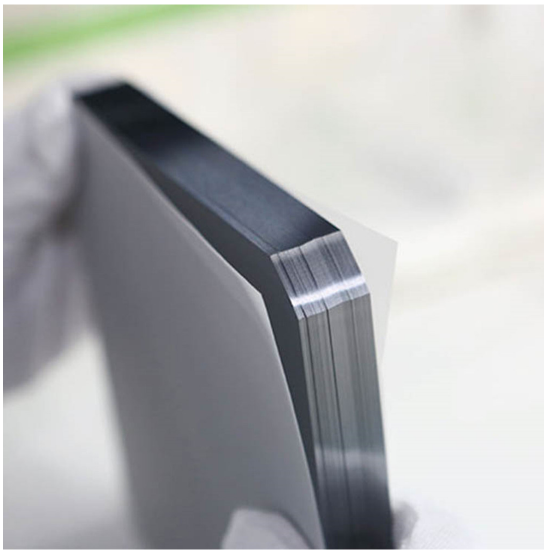
3.4.2 The Float Zone method

The FZ method starts with a polysilicon rod from the Siemens method. The bottom end of the rod is melted by a surrounding heating coil and then connected to a seed crystal. When the heating coil moves upwards along the polysilicon ingot the bottom cools and solidifies while taking on the crystalline structure of the seed crystal, causing the resulting ingot to be monocrystalline. As the heating coil moves upwards, a large portion of the impurities in the ingot follows the molten area. This results in the impurities gathered at the end of the ingot after the process, enabling the easy removal of the impure area of the ingot by simply removing the end of the ingot. As such, the monocrystalline silicon ingots formed by the FZ method has a higher purity than ingots formed by the Czochralski method. However, the FZ method requires more energy to conduct [28]. The Czochralski method is illustrated in Figure 3.3a and the FZ method in Figure 3.3b.

3.5 Wafers

Figure 3.4: Ingots and wafers

(a) Silicon ingots formed by the Czochralski method [33].



(b) Silicon wafers cut from ingots and shaped [34].

After the monocrystalline ingots are formed they are cut down into a shape and sliced into thin slices of monocrystalline silicon, wafers. The wafers are either sliced into the size of a traditional cell or a half-cut cell. Both the ingot and wafers are shown in Figures 3.4a and 3.4b. The wafering can be performed through many different techniques, but the most commonly used rely on sawing. Several evenly spaced out strings, traditionally either made from diamond or steel, are used to saw through the ingots and producing the thin wafers. It is this traditional sawing method that produces the polysilicon kerf as mentioned in Section 3.3.3. There are several wafering techniques that are “kerf free”, invented to reduce polysilicon waste, but they are not implemented at a large scale [35].

3.6 Cells

When the wafering process is complete, the cells can be constructed. The first step is to etch off thin layers of the wafer that has damage traces from the sawing process. When the damaged layers has been removed it is common to etch in a pyramidical pattern on the top surface of the layers to increase the probability of absorbing the solar irradiation [36].

Following the etching, the wafer is then n-doped through gas infusion. This doping only breaches the outer layer of the wafer, resulting in a p-doped core and an n-doped outer edge. After the doping is done the sides are etched off, leaving an n-doped top and bottom surface [37].

The next step is to add an anti-reflective coating to the top surface of the wafer. Afterwards metal contacts are screen printed on top of this, in addition to a back metal contact being screen printed on the bottom surface of the wafer. To fuse all these additional layers, the now constructed cell is fired in a furnace. After the firing, the solar cell is complete [36].

3.7 Modules

The final product is the module. The finished cells are strung together in parallel series, connected by flat metal wire to lead the current. The number of cells depend on the size and wanted power of the module. The cells are placed between two layers of ethylene vinyl acetate (EVA). EVA is a polymer material used to encapsulate the cells, preventing the entry of air and the subsequent moisture formation, whilst letting the solar irradiation through and withstanding the solar degradation over time [38].

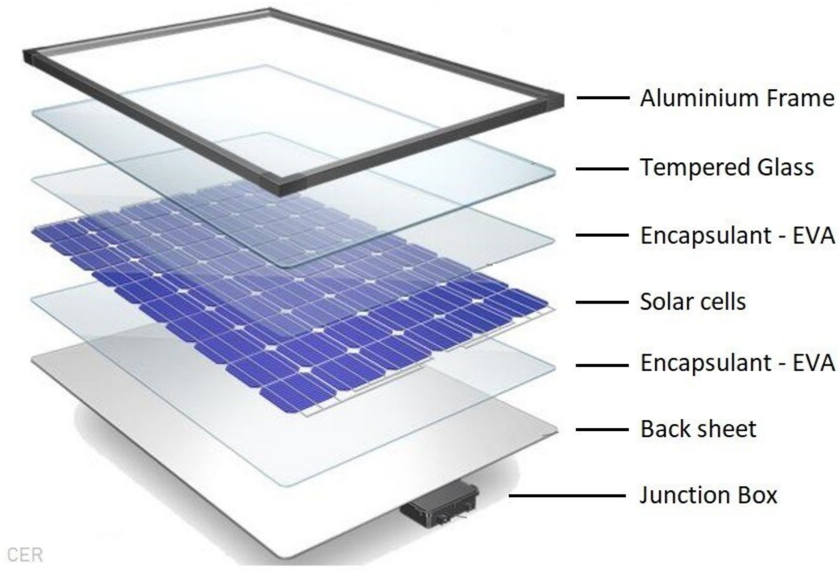


Figure 3.5: The components of a complete solar module [39].

The cells and EVA layers are further layered with a back sheet beneath the cells, a glass layer above the cells and a frame holding all the layers together and sealing them off [39]. The composition is shown in Figure 3.5. This frame is usually made of aluminium as it is a light, but durable metal. The last element is a junction box that houses all the electric component protruding from the module and protecting them from the elements [40]. With all these components in place, the PV module is finished and the chain of production is complete.

4 Sustainability

The UN has defined its sustainable development goals to combat many of the issues the world is currently facing. Several of these goals is directed at or could be met by producing more renewable energy. In addition to the three goals presented in Section 1, goals 7, 12 and 13 are also applicable for the PV industry. Goal 7 and 13 calls respectively for "Affordable and clean energy" and "Climate action", whilst goal 12 is directed towards "Responsible consumption and production" [5]. In today's PV industry, some sectors are not abiding by these principles. How the world meets these goals, will be critical for the future of the both environmental and social sustainability in the PV industry.

4.1 Environmental sustainability

The rapid development of climate change has made it a top priority for many countries to develop renewable energy and reduce the overall carbon footprint (CFP) of the country. As solar energy is renewable, there has not been much focus on optimising the PV industry's CFP. However, even though the energy produced is carbon neutral, the production of the solar panels may not be. As solar energy is the fastest growing energy source, there is good reason for optimising the industry's CFP in order to minimise carbon emissions.

The environmental sustainability of PV panels needs to be examined in relation to other energy sources. The complete cradle to grave emissions from solar energy is way less than that of traditional fossil based energy sources. Compared to other renewable energy sources however, the GWP from solar energy is not the most environmentally friendly option, as shown in Figure 4.1. Solar energy however, has other redeeming qualities such as an easy and cheap installation process, very little damage to nature in the installation area and the possibility to install almost everywhere, which often makes it the most viable renewable energy option [13].

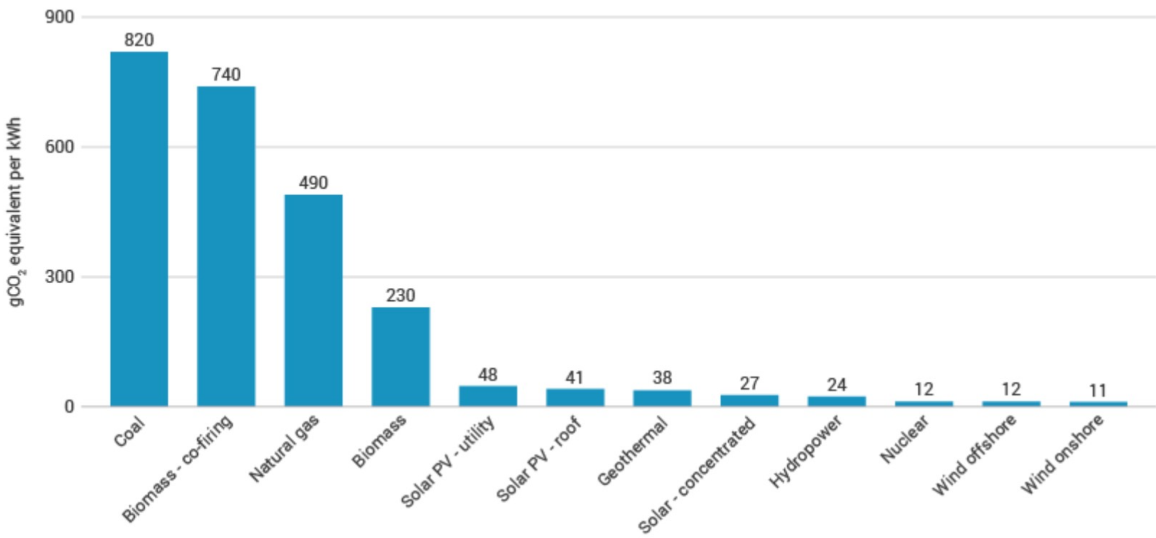


Figure 4.1: Emissions from different energy sources [41].

The emissions from solar power occurs mostly during production, with potentially large differences internally in the solar market. Different panels may have different carbon emissions in the upstream supply chain, due to use of different materials, electricity mixes and production technology. The use of fossil fuel based electricity in the production stages is one of the factors that significantly affects the CFP of a module. As some of the production stages are very energy intensive, especially the purification of silicon and forming of ingot, utilising coal to power these processes would lead to large emissions [17].

China has a large share of the PV production market, as well as a high concentration of coal in their national electricity production. This could affect the CFP of the general PV industry. Xinjiang accounts for 40% of China's coal reserves, making it probable that the PV industry located in Xinjiang utilises even more coal power [3]. The Chinese government has aided the development of large coal power plants in the Xinjiang region and advertised this cheap power source to large manufacturers [42]. As such, several large polysilicon manufacturers are situated close to coal fields and coal power centres. This creates the possibility that the manufacturers may be utilising purely coal power in their production, and not a varied electricity mix [3].

4.1.1 Recycling

As of today, recycling of solar modules is not widely implemented. One reason is that the majority of the solar energy installed still has not reached its life expectancy. Due to the majority of solar modules being implemented the last two decades, most modules have several years left before needing replacement. However, the module recycling industry is expected to grow in the next few years as more and more modules is nearing their end date. Factors that may speed up the recycling rate in the near future is environmental legislation as well as resource depletion and shortages [43].

There is also possibilities for recycling within the production chain. One example of this is the recycling of kerf presented in Section 3.3.3. Integrating recycling within the production would mitigate resource depletion, cut emissions and may also reduce costs. It would be another step towards a circular PV industry.

4.2 Social sustainability

The solar panel supply chain is heavily concentrated in Asia, with the majority located in China. The concern regarding the labour conditions related to the PV manufacturing plants in China is therefore a wide reaching issue. In the last years, reports has been published regarding the treatment of the Uyghur people in the Xinjiang Uyghur Autonomous Region (Xinjiang) in China. The Uyghur people is a Muslim minority in China and native to the Xinjiang region. The Uyghur people has been subject to severe human rights abuses from the Chinese government. This includes forced labour in several industries [44]. In May 2021, the report called *In Broad Daylight* [3] made headlines, as it made the claim that most of the global PV industry is directly or indirectly connected to the use of forced labour through its supply chain.

The report showcased the use of government supported forced labour programs directly targeted at the Uyghur people. The programs come in the form of "re-educations camps", "labour transfer programs" and as initiatives trying to pressure the Uyghurs to assimilate into an Chinese culture and ways of living. The camps are accused of being internment camps, to which the Uyghur people is pressured and threatened to move to and work in. The people affected by labour transfer programs are not placed in camps, merely relocated to a location close to an industry utilising forced labour. The government claims that the programs are a form of work training designed to help the Uyghurs gain labour skills and improve their work ethic. However the directive from local government which indicated the guidelines for these labour programs stated that the programs should:

> "...have organisational discipline in place and implement militarised management to make people with employment difficulties get rid of selfish distractions, to change their long-cultivated lazy, idle, slow, and inconstant behaviours of personal freedom, to abide by corporate rules and regulations and work discipline, and to devote themselves fully to daily production. The government should use iron discipline to ensure that worker cooperation results in a $1 + 1 > 2$ result." [3]

The results of the report were numerous. The US implemented a ban on all goods with part of its supply chain in Xinjiang without definitive proof that forced labour was not used, and several buyers started to look at companies without ties to Xinjiang to buy their panels from [6]. Major manufacturers located in Xinjiang started the work of moving parts of their supply chain to places outside Xinjiang, or proved through internal and external reports that their supply chain was free of forced labour. It is unclear as to how many companies have wilfully participated in forced labour programs, but there is undoubtedly a lot of companies that are indirectly affiliated through the upstream supply chain. It is important to note that the companies that are involved in the use of forced labour are among the largest companies in the world in their respective industries. Therefore it is possible that only parts of their production is affected by forced labour. However, distinguishing the location of production for specific modules' supply chain requires information not publicly available [3].

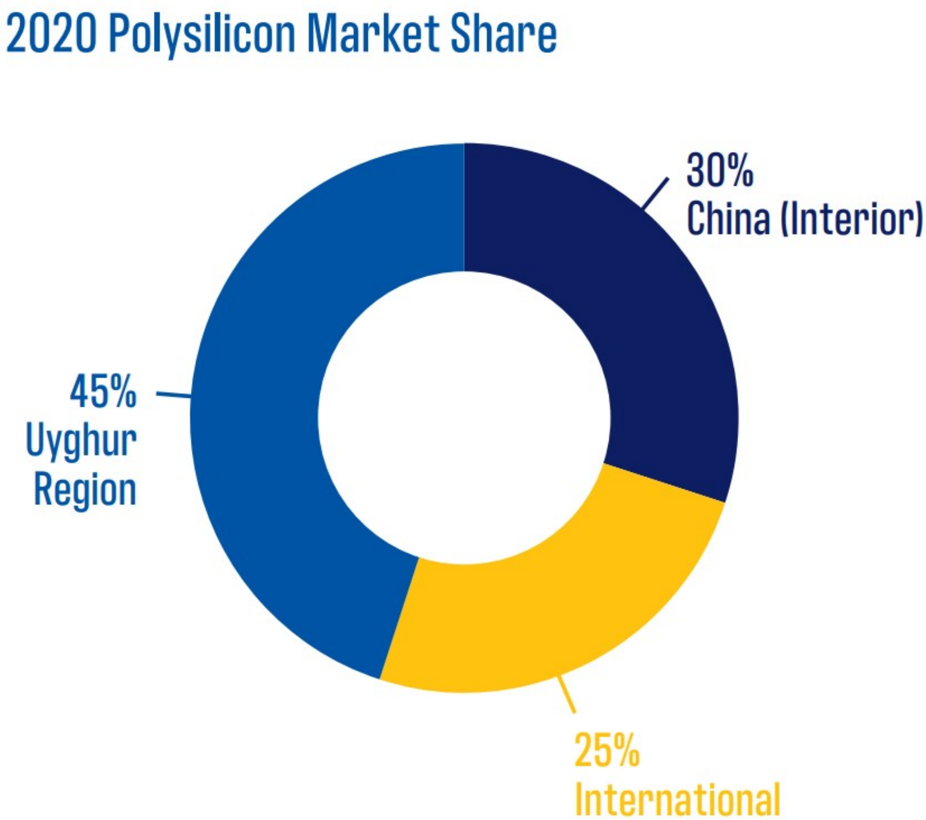


Figure 4.2: Share of polysilicon production in Uyghur regions [3]

The use of forced labour is largely concentrated higher up in the supply chain as it has a higher need of cheap, uneducated labour. Therefore, the industries mining quartz and refining silicon are the ones mostly utilising the “surplus labour programs”. As Figure 4.2 shows, a total of 45% of the worlds polysilicon production in 2020 was located in Uyghur regions. It is therefore likely that large parts of the silicon productions in these areas are affiliated with forced labour programs [3].

4.2.1 XPCC

The Xinjiang Production and Construction Corps (XPCC) is a paramilitary corporate conglomerate operated by the Chinese government. The XPCC has often been described as a state within a state, and is a combination of a private company and an extension of the government. The role of the XPCC is to govern and develop industrial projects in the Xinjiang region, and it is currently operating several industry production camps. These camps offer subsidised rent, cheap power, and help with logistics to the companies who build their business within these camps. Recently the XPCC has been criticised for its involvement in reeducation and surplus labour programs. These programs are widely believed to be a front for forced labour usage [3].

4.2.2 Hoshine

One of the major reasons most PV companies have a risk of exposure to forced labour in their supply chains is because of the company Xinjiang Hoshine Silicon Industry, usually referred to as Hoshine. Hoshine is the world largest MG-Si producer, with an installed capacity of 498 500 tons per year, as of 2021. Evidence shows that Hoshine has employed and actively recruited what is suspected to be forced labour, both through employing from government led internment camps as well as their own labour transfer programs [45, 46]. The company has received significant subsidies from the XPCC to manage it’s own labour skills training and has been named a “key enterprise” by the Chinese government in relation to their labour training policies [3]. Because Hoshine has connections to several major SoG-Si producers, their downstream supply chain is negatively impacted through this link.

5 Market

The solar energy industry has become one of the fastest growing industries in the world. The technology for PV panels have been around for decades, but recently the combination of a growing need for quick and clean energy, as well as technological breakthroughs have led to a rapid expansion of the solar energy market. The market has previously been centred in Europe and the US, but the last 20 years have brought major developments. In the early start of the millennia, China implemented several subsidies and incentives to encourage the production of solar energy. The result of this political push is that as of 2021, as shown in Figure 5.1, around 80% of the total supply chain and production of solar energy is located in China [47, 48]. This market centralisation may lead to issues concerning the worlds dependence on Chinese production and energy self sufficiency.

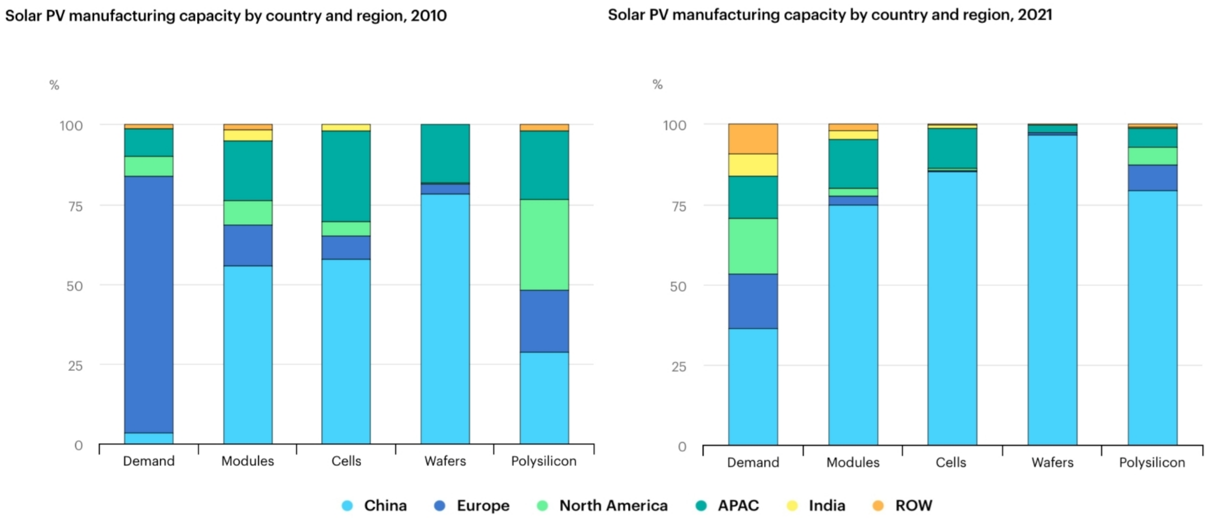


Figure 5.1: Manufacturing capacity by country and region [49].

The exponential growth of the Chinese solar industry was due to the Chinese governments policies. Through this, the Chinese manufacturers was given billions (USD) in low cost loans by the government. Additionally, the manufacturers received large tax credits. This made the Chinese manufacturers able to expand their production as well as their research and development at a much faster rate then their foreign competitors. A result of this was that the price of solar panels dropped drastically, which resulted in many European and American solar manufacturers going bankrupt [47, 48].

A positive result from China's takeover of the marked is the advancement of solar technology and the lowering of the LCOE. The billions provided by the government supercharged the industry. In the period from 2008 to 2013 Chinese modules manufacturers drove down the price of solar with 80%. The large price drop lead to a significant increase in demand, due to solar energy now being profitable [47, 48]. However, this comes at the cost of having the rest of the world depend on one country for the majority of their imported PV products, creating a dependence on China. This is especially significant due to China having complicated geopolitical relationships with certain western countries, the US in particular, in addition to lacking transparency, both in government and industries. With the world aiming to significantly increase the amount of installed solar power, being dependent on one sole country may lead to insecurity in the energy supply chain.

5.1 The PV supply chain

The centralisation of the PV industry has resulted in a rapid development of the market. Several European and American companies have gone bankrupt [50], the technology and efficiency of PV production has been majorly improved and the cost of solar panels have drastically decreased [2]. As introduced in Section 4, the conditions during which much of the supply chain for the PV industry is produced have also recently garnered attention. To give an insight into the PV market, the following section will introduce the current PV market and companies relevant for further studies.

5.1.1 Raw materials

The mining and extraction of quartz for use in PV modules is more geographically dispersed than many of the other stages. However, there is a significant lack of transparency and open documentation in the industry. This results in only vague overviews of quartz extraction being available. Major quartz extraction sites are operated in Europe, China, Brazil and North-America, with the largest quartzite quarries in the world found in Norway and South America [51, 52, 53]. Elkem and Ferroglobe are large companies operating in Europe, with Ferroglobe also extracting quartz in North and South-America [54, 55]. Figure 5.2 shows one of Elkem's quarries in Norway. Rima is another major company operating in South-America, with its centre of operations in Brazil [56].

Figure 5.2: One of the worlds largest quartz quarries, situated in Tana in northern Norway [55].

Relating to the PV industry, it is indicated that large quartz deposits are located in China. These are likely the source of the quartz utilised in the Chinese PV polysilicon industry. The Xinjiang province is estimated to hold 10% of China's reserves of vein quartz used in the manufacture of metallurgical-grade silicon. With these large deposits being mined in Xinjiang, and the lack of transparency and public documentation in the quartz industry, there is a probability of forced labour being used [51, 3].

It is difficult to establish exactly which companies that supply the PV industry with raw materials, due to the lack of transparency. However, some of the locations are known, such as the Shanshan Stone Industrial Park. This is the cite of major raw material extraction and refining, located in Xinjiang, with Hoshine having a large silicon processing park within Shanshan Stone Industrial Park [3]. Another one of Hoshine's suppliers is Xinjiang Tianye. The company's annual report from 2018 indicates their participation in labour transfers and vocational training programs, among others [57]. However, it is not known if Tianye supplies Hoshine with raw material or other chemical products for Hoshine's other business ventures [3]. As such, it is unclear if Tianye directly affects the sustainability of PV supply chains.

5.1.2 Metallurgical grade silicon

The production of MG-Si is mainly focused in China, with lesser production in Norway, the US and Brazil, among others. Figure 5.3 shows the market share distribution from 2015 to 2020. The factories are mostly located close to quartz mines, or port cities to have easy access to transported quartz.

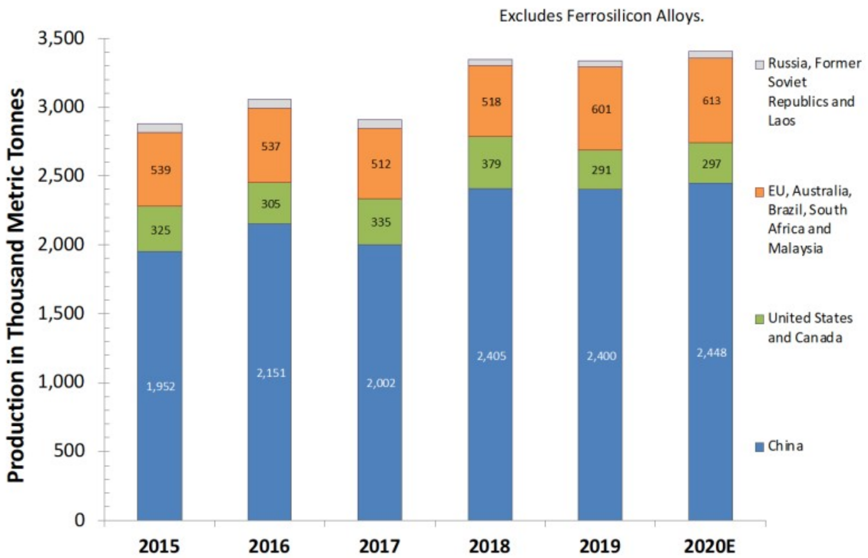


Figure 5.3: The distribution of MG-Si market shares divided by regions [50].

From Figure 5.3 it is evident that China has a majority market share of MG-Si of approximately 70%. While China has the majority MG-Si market share in the world, Hoshine is reported to be dominating the Chinese MG-Si industry [3]. In 2021 Hoshine was reported to be the worlds largest MG-Si producer [58]. With Hoshine having such a large production capacity and allegedly engaging in human rights violations against the Uyghur people, the company might expose a large part of the downstream suppliers to forced labour.

Another MG-Si supplier possibly affecting the social sustainability of its downstream supply chain is Xinjiang Sokesi New Materials Company, commonly known as Sokesi. The company supplies polysilicon manufacturer Daqo with 47% of their MG-Si [59]. Regarding forced labour, the company is reported by media to have engaged in government sponsored labour transfers, but the company itself has not confirmed this [3].

5.1.3 Polycrystalline silicon

Up until 2005, the polysilicon market was centred around companies in Germany, US and Japan. After 2005, China has had a rapid growth in market share, boosted by national policy and regional subsidies, and is as of 2021 responsible for 72% of the global production capacity. A majority of the polysilicon production in China is located in Xinjiang. The province produces 54% of China's polysilicon, which equates to 39% of the global market production. Currently, seven of the top ten companies producing polysilicon is located in China. The largest of these being Tongwei, Daqo, GCL-Poly and TBEA, as shown in Figure 5.4. The German company Wacker Chemicals has the highest, non-Chinese market share of about 13%. The US and Japan owned Hemlock Semiconductor and South Korean owned OCI Malaysia has a combined 9% market share [50].

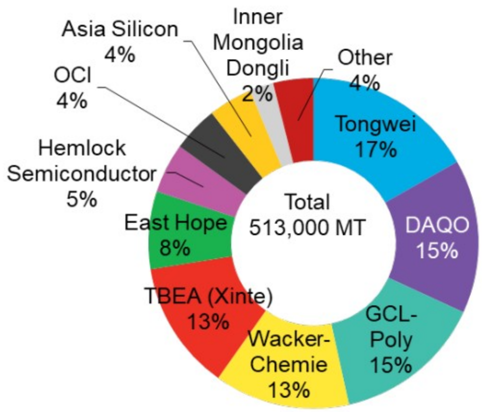


Figure 5.4: The global market share of polysilicon production [50].

There is growing concern amongst polysilicon suppliers in China surrounding the US sanctions regarding modules with ties to Xinjiang in their upstream supply chain. This has resulted in multiple factories planned outside the province. The most prominent new manufacturing location is currently Inner Mongolia which has recently expanded their hydro power capacity, enabling polysilicon manufacturing to become cheaper and less polluting [50]. The projected polysilicon production in Inner Mongolia is shown in Figure 5.5.

The worlds largest polysilicon company, Tongwei, does not have manufacturing plants in Xinjiang. Tongwei also does not have any direct links to forced labour, with the exception of being named as a customer on a investor forum by Hoshine in 2021 [60]. Daqo however, the second largest polysilicon manufacturer in the world, both operates in Xinjiang and has direct links to XPCC and Hoshine. Regarding the XPCC, Daqo invested in the XPCC's Shihezi Industrial Park. Following this, Daqo has acquired subsidies, incentives, energy, and "special price negotiation dispensations" from the XPCC [61]. Regarding Hoshine, Daqo is named one of Hoshine's largest customers [3], exposing themselves to indirectly to forced labour. The only evidence of direct exposure is Daqo's own reports of participating in "labour placements", a term sometimes used by Chinese government and companies to refer to forced labour [62]. However, Daqo has strongly denied these accusations, claiming them to be based on a mistranslation of their programs supporting skilled workers hired by Daqo in their move to Xinjiang.

Another polysilicon manufacturer receiving large parts of their supply from Hoshine is GCL-Poly [3]. This causes indirect exposure to forced labour through the supply chain, but GCL-Poly has several cases of direct exposure as well, mainly through a subsidiary company, Xinjiang GCL.

There has been several reports, both through local media and from Xinjiang GCL themselves, that the company has employed “coerced surplus labourers” in their manufacturing facilities [63].

The manufacturer TBEA not only has manufacturing plants in Xinjiang, but is also headquartered in the province, unlike the other big Chinese polysilicon manufacturers [3]. The company has a subsidiary company manufacturing polysilicon called Xinte. In addition to labour transfers to TBEA’s manufacturing plants, the company also strongly engages in other Uyghur assimilation initiatives. These initiatives are accused of focusing on erasing the Uyghur culture and replacing it with traditional Chinese culture. Through these, TBEA refurbishes Uyghur homes to resemble Chinese homes, installs TV’s in Uyghur home to allegedly ensure the families have access to government propaganda, and placing TBEA employees as “relatives” in Uyghur households to educate and monitor the families [64]. Despite TBEA supporting labour transfer programs, it is not known to which extent Xinte utilises these.

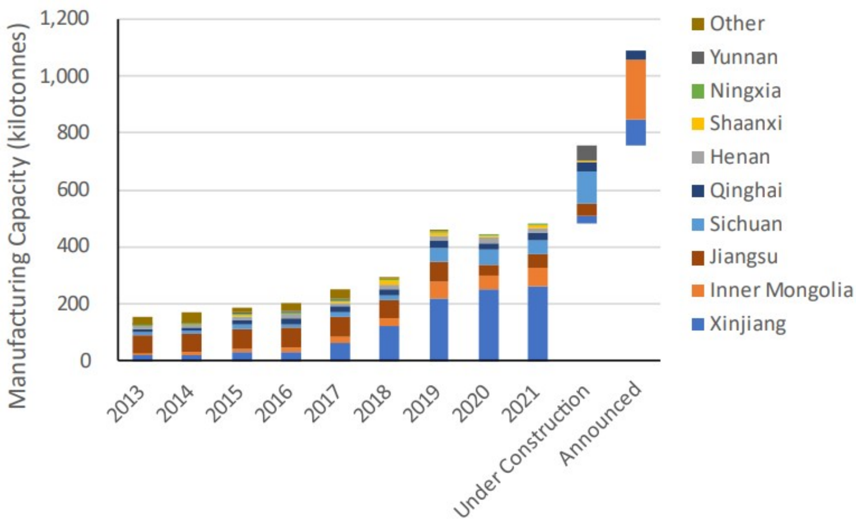


Figure 5.5: The production capacity of polysilicon in Chinese provinces [50].

In the European market, there are mainly two prominent manufacturers in the polysilicon industry. The German company Wacker Chemie, with a production capacity close to 60 000 metric tons, and Norwegian REC Solar. Whilst Wacker produces SoG-Si in the traditional way, using the Siemens process to achieve the purity demanded for SoG-Si, Rec Solar buys waste kerf produced from sawing SoG-Si ingots in China, and purifies this waste material back into SoG-Si ingots. This process is not only one of the most energy efficient polysilicon production methods, but it also reduces and recycles the waste from solar industry, making the process even more sustainable [65]. REC Solar might be the only manufacturer in the world utilising silicon kerf. In 2019 the international PV industry produced an estimated 200 000 tons kerf, whereof REC Solar uses 8 600 tons in their production [23, 25].

The Norway based polysilicon company REC Silicon is the only major company in the world that utilises FBR technology on a larger scale. While Norway based, the company only has manufacturing plants in the US and China. The FBR technology is utilised by one manufacturing plant in Washington, US, and one in Shaanxi, China [66].

5.1.4 Ingots and wafers

The production of ingots and wafers is energy and labour intensive, and are therefore more dependent on large scale production with cheap labour and energy. The wafer industry is dominated by Chinese companies, as presented in Figure 5.6. In 2021, only 10 GW of ingots and wafers were produced in the rest of the world, whilst close to 300 GW was produced in China. The non-Chinese production is mostly based in Taiwan, but several Chinese companies are looking to Thailand and Vietnam do expand their production. There are ten Chinese companies producing about 98% of the total manufacturing capacity in the world, and the companies LONGi, GCL, Zhonghuan and JinkoSolar alone stands for 80%. Unlike the polysilicon industry, the wafer manufacturers are not heavily centralised in one region of China. Several regions have substantial wafer production, but Jiangsu has the largest capacity of 28% of production [50].

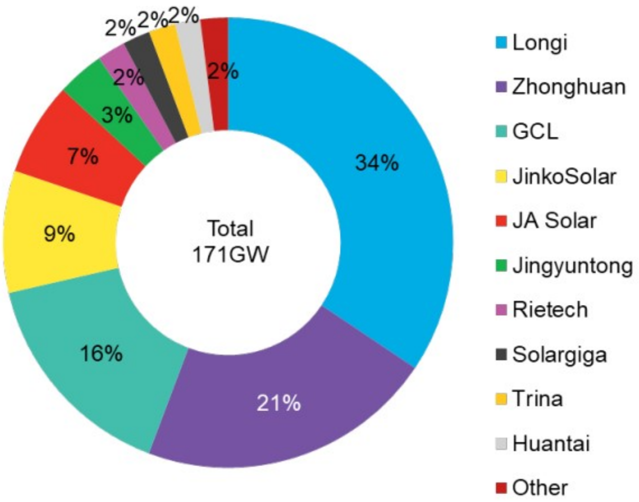


Figure 5.6: The market shares of the ingots and wafer production divided by companies [50].

The Chinese domination of the wafer market is mostly due to severely beneficial political incentives. In 2010, the US had several promising wafer companies, and was able to satisfy 80% of its domestic demand. During the following years, competing with the Chinese market became almost impossible. This was due to the cheap energy prices, a centralised supply chain and the access to labour and area made available by Chinese government policies. Thus, by 2016 all the US companies had stopped wafer production [50].

JA Solar is the worlds fifth largest manufacturer of silicon ingots and wafer. The company does not manufacture in Xinjiang, but do have a lease agreement with XPCC through 2040, concerning several power plants JA Solar operates in Xinjiang. There is no evidence that JA Solar engages in any forced labour programs. However, being a customer of Daqo, Xinte and GCL-Poly, JA Solar's supply chain is at risk of being exposed to forced labour [3].

The manufacturer Wuxi is not one of the largest in China, but it is a significant supplier for Risen Energy. While in 2008, Wuxi established a subsidiary in Xinjiang, Xinjiang Suntech Energy Engineering Co., Ltd.307, this subsidiary does not produce any PV related products. The subsidiary focuses on power generation plants and engineering. As such, Wuxi does not have any direct connection to Xinjiang or forced labour. Indirectly, Wuxi is exposed to forced labour through being supplied by Daqo, GCL-Poly and TBEA [3].

In the European market, the majority of the wafer capacity is located in Norway. In 2022, almost 1.7 GW were produced using Norwegian hydro power as a clean and cheap energy source. Norwegian Crystal is a leading company in wafer manufacturing and are planning an expansion of production in the following years. Norwegian NorSun is also an established wafer manufacturer in the European market [65].

5.1.5 Cells

The manufacturing of cells is slightly less dominated by China than the two previous steps in the supply chain. About 80% of the global cell manufacturing is located in China, with the Jiangsu province being responsible for around 41% of said production [50]. The production of cells is largely automated and is therefore more reliant on educated labour than the previous steps in the production chain. The production of cells are often located close to module manufacturing. Considering the fact that cells and modules are more often shipped internationally, the two Chinese provinces with the most production Jiangsu and Zhejiang, are located near the coast.

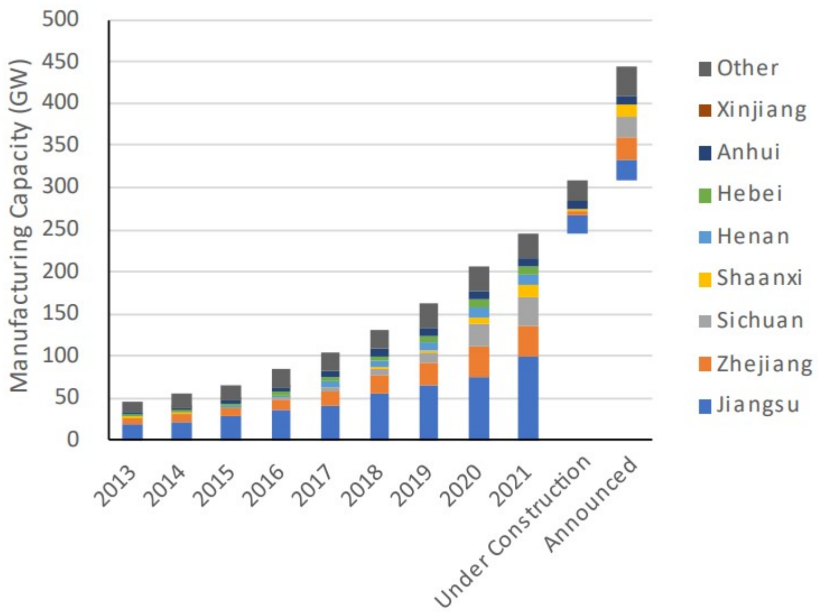


Figure 5.7: The production capacity of cells in Chinese provinces [50].

The largest non-Chinese cell manufacturer in 2020 was Hanwha Qcells [50] with production in the US, South Korea and Malaysia, in addition to China. The majority of non-Chinese production is still located in Asia, commonly to be close to wafer production. The European cell market is close to non-existent, with only a few smaller companies present, such as Meyer Burger and 3Sun [67].

As presented in Figure 5.7, only a small part of the PV cell production in China is located in Xinjiang. JA Solar and Wuxi are both cell and module manufacturers, in addition to ingot and wafer manufacturers. Their social sustainability is therefore as described in Section 5.1.4. The Chinese cell and module manufacturer Risen is indirectly exposed to forced labour in their upstream supply chain through Wuxi.

5.1.6 Modules

The last stages of the PV supply chain, from ingot to module manufacturing, is largely vertically integrated. Whilst it is not necessary for module manufacturers to operate close to the other steps in the production chain, it does still benefit from certain synergies that large scale vertical production creates. Jiangzu and Zhejiang are responsible for around 68% of the total manufacturing of modules in China, and as mentioned earlier, much of the whole value chain is produced in the same provinces. The government subsidies, cheap energy and centralisation of knowledge and experience is amongst the synergies that the companies benefit the most from [50].

Module production is the least Chinese dominated process in the supply chain. Figure 5.8 shows the dispersion of module manufacturing capacity outside of China. The components needed to produce a module is easily shipped and around 33% of module manufacturing happens outside of China. This manufacturing is mostly located in other Asian countries such as Vietnam, India and Korea. Many of the large Chinese manufacturers have planned projects in Thailand and Vietnam. These companies are often located close to the borders to accommodate for easy transportation from Chinese component producers [50].

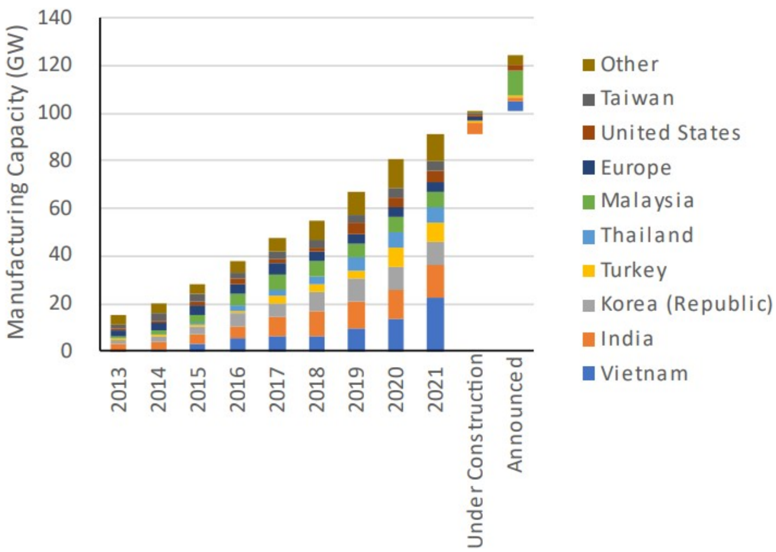


Figure 5.8: The module production capacity in non-Chinese countries [50]

The combined module capacity of the US and Europe in 2021 was less than 10 GW [50]. Previously, the US had a significantly larger capacity for module production, which was out competed by cheaper Chinese manufacturers. However, the US based production is seeing an increase, largely due to new government policies.

5.2 Policies and certifications

In a rapidly expanding and developing industry, such as the PV industry, the introduction of government policies to steer the industry growth is a necessary and standard practice. This is especially the case when an industry begins being largely dominated by one region or country. China's development to control more than 80% of the PV supply chain has been detrimental to the PV industry outside of China. Subsequently, the EU and the US has started taking steps to counter act this development.

5.2.1 REPowerEU

On the 18th of may 2022, the REPowerEU plan was introduced to European Parliament. The main background for the plan was to decrease the dependence on Russian oil, gas and coal imports, following the war in Ukraine. REPowerEu's goal is to increase energy independence in the EU by establishing new supply chains for renewable energy. This will include increasing EU's manufacturing capabilities of solar energy, wind energy and batteries, an acceleration of renewable energy projects, as well as introducing diverse supply routes and energy saving measures [1]. The basics of the REPowerEU plan is described in Figure 5.9.

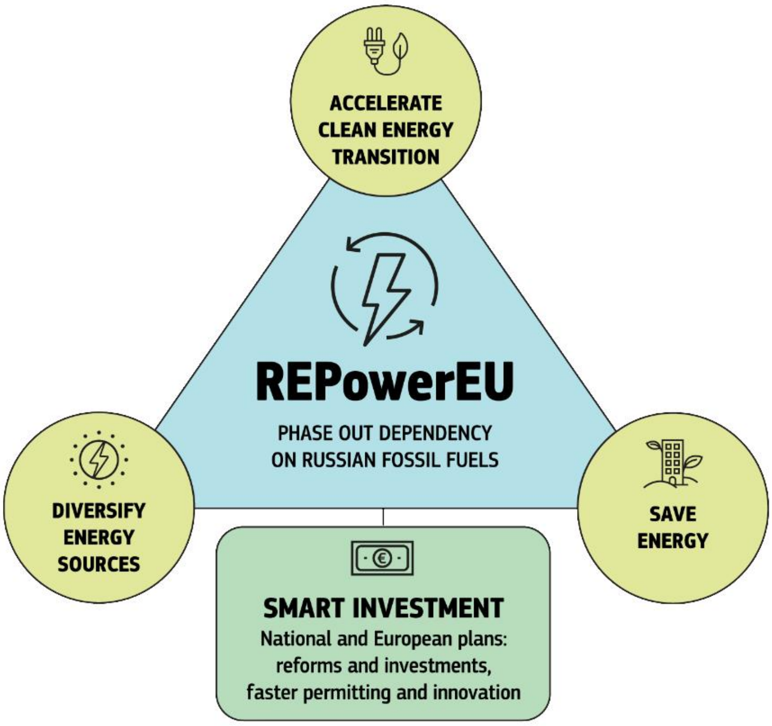


Figure 5.9: The REPowerEU plan [1].

The part of REPowerEU concerning solar power is called the EU Solar Energy Strategy. This strategy is divided into four main focus areas. The first is called the European Solar Rooftops Initiative, and it's goal is to gradually increase the requirements regarding installed solar power on rooftops. The goal is to make installing solar power on industrial and residential rooftops simpler, as well as compulsory on buildings of a certain size. The plan aims to have up to 320 GW of solar installations before the end of 2025 [68].

The second focus area is streamlining and accelerating the permitting procedures for implementing solar installations and production. This is done to assist the establishment of European produced PV panels. It is an important step to reach the goals established in REPowerEU of an installed manufacturing capacity of 30GW fully located in Europe by 2025. This is to be achieved through a package of legislative proposals, recommendations and a guidance document [1].

Thirdly, the strategy entails the establishing of an EU large-scale skills partnership. This entails gathering relevant stakeholders to work towards ensuring the availability of skilled workers in the renewable energy sector in the EU, as well as maintaining development and capacity building for the existing workers. Its estimated that the EU Solar Energy Strategy will lead to 400 000 direct and indirect jobs, large portions of which will need to be filled with skilled labour [69].

Figure 5.10: The goals presented by ESIA [1].

The European Solar PV Industry Alliance (ESIA) is the fourth and final segment of EU's solar energy plan. The alliance is inspired by the success the European Battery alliance, which has helped streamline the manufacturing of several new battery factories in Europe. The goal of the PV alliance is to act as a common interest group between the industry, and the financial and political stakeholders. The alliance will gather financial funding from private and public investors, and help disperse these funds to make sure the European supply chain will remain environmentally and economically sustainable. Through this, the initiative aims to increase and diversify the manufacturing capabilities in the EU [1].

ESIA will also work at streamlining new laws and regulations, as well as ecodesign criteria to make sure the the laws and regulations are not limiting the growth of the new market. The general goals of ESIA is illustrated in Figure 5.10. The aim of this alliance is to regulate and guide the solar market in Europe in a sustainable social, economical and ecological direction [69].

5.2.2 The Inflation Reduction Act

It is not only the EU making efforts to diversify and secure their energy supply and supply chains. The US has made solar energy production an important focus in its industry development for the coming years [70]. As a result of this the US has introduced high tariffs and regulations on certain Chinese imported goods [6]. This is a part of the process of decoupling the interdependence of the two economies. The goal of the tariffs is to increase the competitiveness of US made goods compared to cheaper goods imported from China, as well as increasing the energy self sufficency of the the United States.

The most important driving factor for the development and deployment of a PV industry in the US is the Inflation Reduction Act (IRA), which was signed into law by President Joe Biden on August 16, 2022. The IRA is an amendment to the Build Back Better plan, and includes spending directly geared towards investment in clean technology energy solutions, amongst other things. The purpose of this act is similar to that of REPowerEU, and aims to establish national manufacturing and supply chains for solar energy, as well as ramp up installation of solar energy [70]. The impact of the IRA is presented in Figure 5.11.

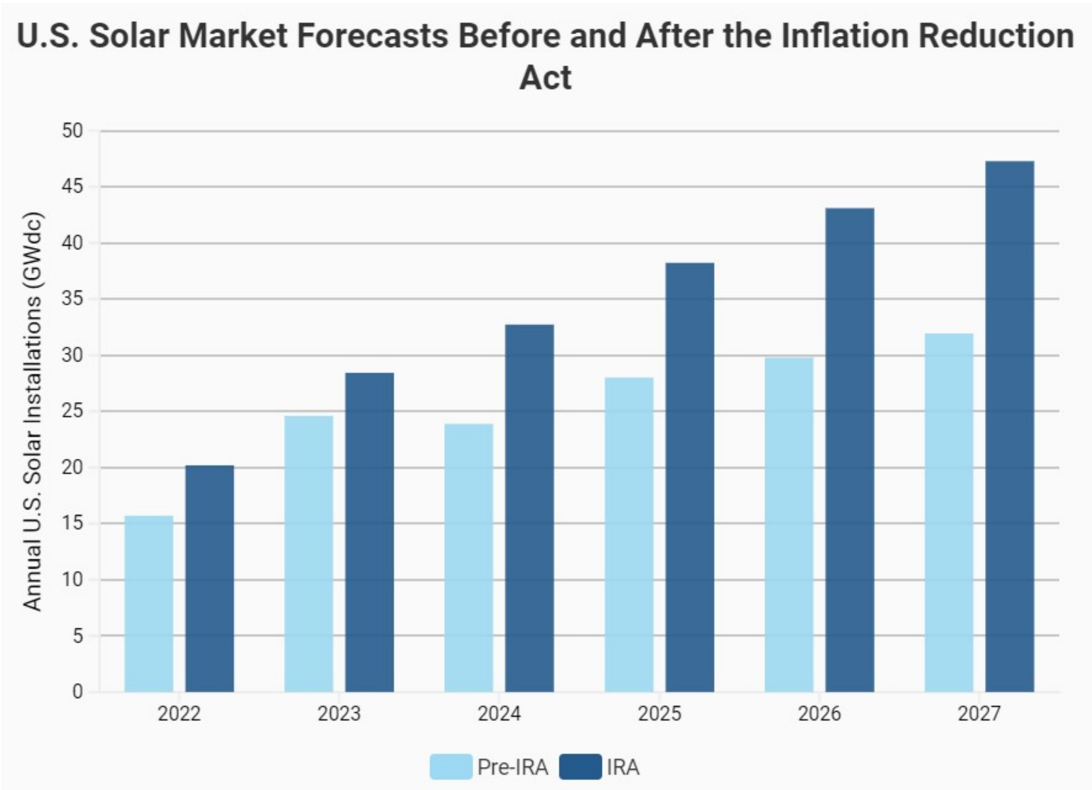


Figure 5.11: The US PV market outlook with and without IRA [71].

One of the way the IRA incentivises solar energy investments is through the Solar investment tax credits (ITC) and the advanced manufacturing production tax credit (PTC). The ITC is a tax relief given for installation of certain solar systems. The tax reduction is set at 30% of the cost of the system and is designed to incentives the installation of residential and large scale solar systems. The PTC is aimed at at the investors and production companies. It is also a tax reduction, and it scales based on how much of certain products are produced. For solar investments, the tax credits are given to producers of polysilicon, wafers, cells, modules, torque tubes, polymeric backsheet and solar trackers. Thereby the whole supply chain is incentivised. The size of the tax credit is predefined for each component listed. The PTC is also eligible for installation, and is in that case based on total production of energy for the first ten years. The major difference between ITC and PTC is therefore that ITC has an immediate payout, whilst the PTC has a regular payout over the next ten years [72].

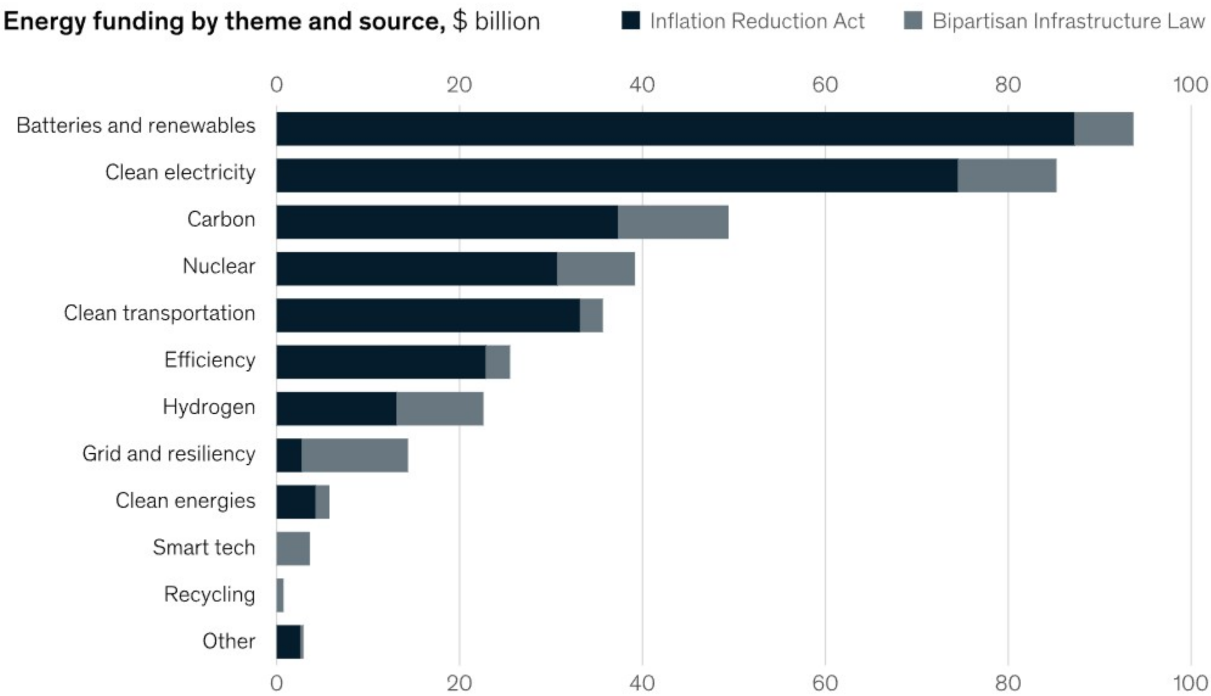


Figure 5.12: The estimated investments from the IRA [73].

The PTC is also directed towards wind and battery production. Its believed that these government issued incentives will provide a significant boom to the solar and renewable energy industry in the US. The estimated investments to the different energy sectors due to IRA is presented in Figure 5.12. For the EU, an American based supply chain may help strengthen the energy independence from China and Russia [72].

5.2.3 Forced labour policies

On December 23, 2021, President Biden signed the Uyghur Forced Labour Prevention Act (UFLPA) which effectively forbids the import of every product with part of the supply chain located in Xinjiang, China. The decision was made based on new information regarding the social injustices committed by the Chinese government in Xinjiang. The act was made to ensure that products used in the US, like solar modules, were not made using forced labour. The companies that produce in Xinjiang and still want to export to the US market have to extensively prove that their whole supply chain is free of forced labour [6]. UFLPA has lead to a reduction in the installation of solar energy in the US. The ban on Xinjiang based modules being implemented simultaneously with the IRA has created a very beneficial environment for the emerging US-based PV industry.

As of today, the EU has not brought into effect any bills comparable to the IRA in the US. The European Commission has proposed a ban of any products utilising forced labour. The ban proposal has been sent to the European Parliament, but is not yet processed [74]. The EU has however implemented sanctions toward a few of the Chinese government officials with the greatest influence and responsibility over the human rights violations committed against the Uyghur people [75].

5.2.4 CFP certifications

One trend in PV market regulation is the emergence of CFP certifications. The CFP certifications are implemented as a response to governments creating strong regulations on the allowed climate impact of an imported product. France and South Korea have recently implemented regulations for larger solar projects that give advantages to companies with lower CFP's, which needs to be proven through specific certification companies. These regulations help companies that are not able to compete with the major Chinese companies in price, but are produced more sustainably, gain access to the market [8].

In France, the company CERTISOLIS has the sole responsibility of approving module manufacturers and issue the certification, called the "Simplified Carbon Assessment". This is then submitted to the Energy Regulatory Commission (CRE), the independent public body appointed to regulate France's electricity market [7].

Following the implementation of the french CFP certification, some other countries has announced plans to follow suit. South Korea and France are currently the only countries to implement PV CFP regulations [8]. Since South Korea's CFP methodology was introduced, several companies has acquired certification for specific panels, among them JA Solar, Risen Energy and Hanwha Qcells [76]. After obtaining the certifications, Qcells released a press release expressing the fact [77]. This is an example of the CFP certifications working as an incentive in the industry, as they also have the function of advertising and improving the reputation of the companies, in addition to gaining advantages in markets.

5.3 Future market

The international PV market is in a phase of significant change. This is due to several factors. The first being the continuous development of PV technology and the growing need for solar power in the world. Secondly, the western world wishes to decrease their dependence on China in the PV industry. The exposés concerning forced labour of the Uyghur people in China is a recent additional factor contributing to the rapid changes in the market.

A significant change seen in the industry is companies moving parts of their production and supply chain out of Xinjiang. This is likely done both to avoid import restrictions, such as the ones applied in the US, and to improve their general reputations. Some companies, such as Hanwha Qcells, aim to move their supply chain out of China entirely [78]. The majority of the companies moving production, however is moving out of Xinjiang to other Chinese regions, especially to Inner Mongolia [50].

The manufacturers moving their production is likely a result of the consumers, downstream companies and governments having an increased knowledge about the human rights violations in the industry. A trend seen in the market is companies installing solar power acquiring about the supply chain of the modules, wishing to acquire modules with the "cleanest" supply chains. Some sources predict that this attention to social sustainability in the industry may lead to PV module social certifications, certifying the modules not being produced using forced labour [79].

Regarding certifications, it is predicted that more countries will follow the example set by France and South Korea and establish CFP certification requirements [8]. This could create incentive for the industry to decrease their emissions and improve the environmental sustainability of the industry. It may also lead to increased research and development in the industry, so as to develop new, low-carbon technologies.

A general consensus in the market is the future importance of recycling of PV modules [80]. There are clear trends of production, as well as research and development, focusing on creating more recyclable modules and better recycling technologies and systems. Recycling within the chain of production is less focused on. While reducing large amounts of polysilicon produced, and therefore significantly reducing emissions, there are no major announcements of companies adopting kerf recycling processes in their production, or the use of FBR technology in polysilicon production [66].

6 Companies

The goal of this report is for it to be used as a comparative assessment, with the intention of helping Aneo make informed decisions about its solar module suppliers. A current supplier of solar modules for Aneo is JA Solar. There are several smaller PV manufacturers located in Norway and EU, but since their production capacity is very limited, these have not been chosen as a part of the comparative life cycle assessment. Instead Risen Energy, which is another Chinese company and Hanwha Qcells which is a major manufacturer from South Korea has been chosen for the assessment.

6.1 JA Solar

JA Solar is a Chinese solar company. The company's business covers silicon wafers, cells and modules. The whole productions chain is based in China except from two relatively small manufacturing facilities in Malaysia and Vietnam. Since 2005, when the company was founded, they have produced 115 GW of solar modules (as of Q3, 2022). This makes them the third largest solar company in the world [81].

Table 6.1: JA Solar's installed capacity, both current and projected.

Location	**Cells [GW]**	**Modules [GW]**	**Projected Cells [GW]**	**Projected Modules [GW]**	**Sources**
Hebei, CN	6	1.5	10	10	[82][83][84]
Anhui, CN	3	3	-	-	[85][86]
Shanghai CN	-	3	-	-	[87]
Zhejiang, CN	5	10	-	-	[88]
Yunnan, CN	5	10	-	-	[89]
Bac giang, VN	1.5	3.5	-	-	[90]
Penang, MY	1.5	-	-	-	[90]
Arizona, US	-	-	2	2	[91]
Jiangsu, CN	6	6	10	10	[84]
Inner Mongolia, CN	-	-	30	10	[84]
Total	28	37	52	32	

In JA Solar's own sustainability report for the year 2021 they have listed all of their manufacturing bases. This encompasses a total of 12 manufacturing bases, where ten of them are located in China and the last two in Vietnam and Malaysia. Table 6.1 shows all the production found from the 12 manufacturing bases JA Solar had in their sustainability report sorted into the provinces they are based in. The table also shows projected installation capacity within the next five years [76].

6.1.1 Supply chain

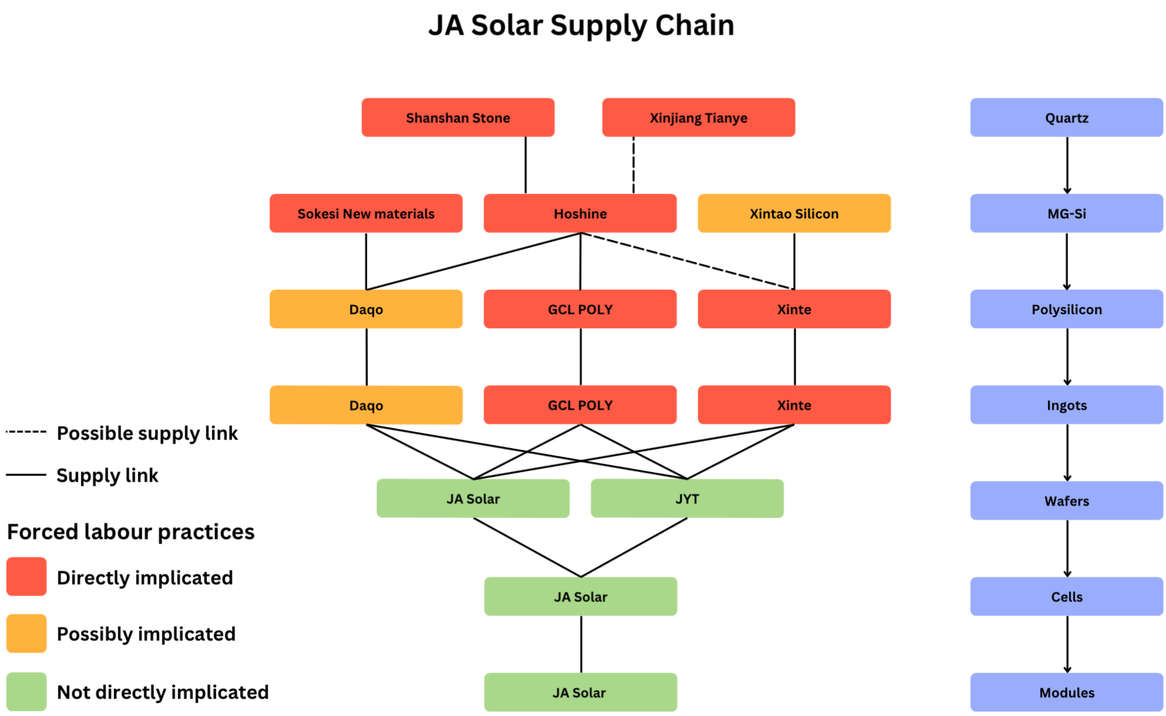


Figure 6.1: The supply chain of JA Solar modules.

Figure 6.1 shows JA's supply chain from quartz extraction to finished modules. The companies represented in Figure 6.1 are the main actors in the supply chain and have deals that are available publicly. There may be other companies in the supply chain, but there are no public record of such deals. Additionally, the companies in the upstream supply chain may supply their products through subsidiary companies which has not been confirmed and is therefore not represented in the figure [3].

The colours in Figure 6.1 reflect the degree to which the company is implicated in the use of forced labour. It is based on results and findings in the report *In Broad Daylight* [3]. Red indicates there is proof of forced labour usage in the company's production. The yellow colour indicates the companies have been accused of using forced labour with some evidence raised against them, but not sufficient evidence to be certain of forced labour usage. These companies have disputed the accusations, and because of uncertainties they have been marked yellow. The green companies have no known connection to direct use of forced labour.

The first stage of the supply chain is quartz extraction. This is reported to be supplied by the Shanshan Stone Industrial Park and possibly by the company Xinjiang Tianye. When the quartz has been extracted, it is passed on to Hoshine, who refines it to MG-Si. For refining MG-Si to SoG-Si, JA has three companies in the supply chain, Daqo, GCL Poly and Xinte. Daqo is supplied MG-Si by Sokesi New Materials and Hoshine, GCL Poly is supplied by Hoshine, and Xinte is supplied by Xintao Silicon and possibly Hoshine. The three polysilicon manufacturers also produces ingots before supplying this to the wafer manufacturers. JA Solar does have some wafer production themselves, but not enough to cover their cell production. The majority of the wafers are supplied by JYT. Both cells and modules are manufactured by only JA Solar [3].

6.1.2 Future supply chain

JA Solar has announced several plans to expand their PV manufacturing capacity as shown in Table 6.1. The plans is mostly focused on expanding their capacity within China. JA solar is also planning to open a new manufacturing base in the US, which will have a cell and module capacity of 2 GW. They still have ongoing deals with large polysilicon companies, one of the known agreements is with Xinte to buy 97 000 tons of polysilicon through 2025 [3].

6.2 Risen Energy

Risen Energy is a rapidly growing company based in China. As of 2021 it was ranked as the 7th biggest module manufacturer in the world [3]. Its focus has primarily been on the production of solar cells and modules, but very recently it has started to produce parts of the whole supply chain for PV panels. They have stated that this is to reduce the effects a volatile polysilicon market has on the whole PV supply chain [92]. Risen currently has five operational production bases with the combined production of 22.1 GW installed capacity for cells and modules. Table 6.2 shows the current and projected installed capacity for Risen Energy. The only manufacturing location not located in China is in Malaysia.

Table 6.2: Risen Energy's installed capacity, both current and projected.

Location	**Cells [GW]**	**Modules [GW]**	**Projected Cells [GW]**	**Projected Modules [GW]**	**Sources**
Malaysia, MY	3	3	0	0	[93]
Zheijang, Yuwi, CN	5	5	15	15	[93] [94]
Zheijanf, Ninghai, CN	4.1	4.1	15	15	[93] [95]
Jiangsu, CN	5	5	4	6	[93] [96]
Anhui, CN	5	5	0	0	[93]
Inner Mongolia, CN	0	0	10	3	[97]
Total	22.1	22.1	44	39	

As previously stated, the most common solar panel on the market is monocrystalline panels with half-cut cells. Risen has a large production of these, but the last couple of years, they have expanded their production to focus on hetero-junction (HJT) cells. These panels are a combination of monocrystalline panels and thin film technology. This panel is called hyperion and has a module conversion efficiency of 23.65 % and a carbon footprint of less than 400 kg CO_2/kWp [93]. This very low carbon footprint was made possible by combining the HJT technology with new steel frames instead of aluminium. Steel is 4.5 times less polluting on a weight basis which result in less polluting frames [93]. Another testament to Risen's environmental sustainability is the french simplified carbon assessment, that was granted to their "Titan" panel in 2021. This certification is highly regarded on the international market [92].

6.2.1 Supply Chain

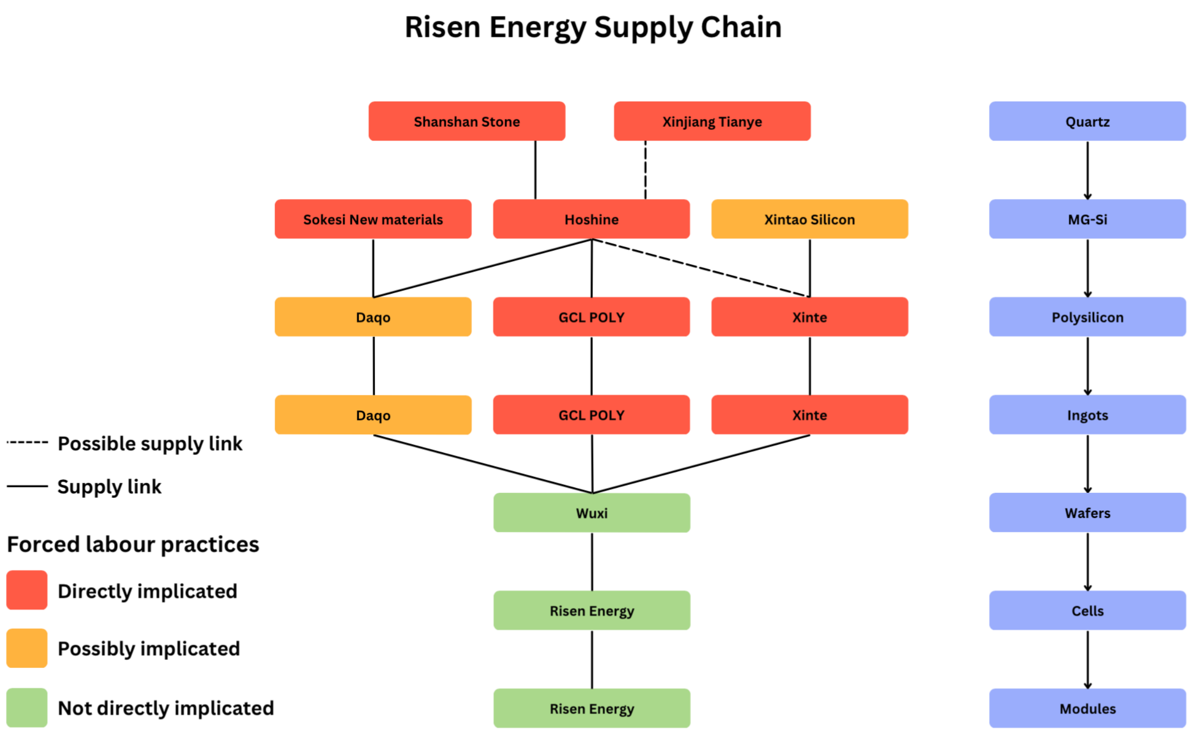


Figure 6.2: The supply chain of Risen Energy modules.

The supply chain for Risen is in many ways similar to that of JA Solar. As shown in Table 6.2, Risen does not have any current or planned manufacturing in the Xinjiang province. It is however indirectly connected to silicon production in Xinjiang through its contracts with Wuxi which in turn get silicon from Daqo, Xinte and GCL-Poly. These polysilicon suppliers are all connected to Hoshine, which is a major producer in the Xinjiang area and has direct ties to Shanshan Stone Industrial Park and Tianye. Both of these companies have direct implications of forced labour. Daqo is also supplied by Sokesi which has been tied to the use of forced labour in their production. Xinte is directly tied to Xintao, which possibly utilise forced labour in their production. The upstream companies are all among the largest producers in the world. There may be some smaller companies that has deals with Risen, but these connections have not been proven. As such, the companies shown in Figure 6.2 are regarded as the main actors in Risen's upstream supply chain [3].

To ensure the sustainability of their primary supply chain, Risen added Corporate Social Responsibility (CSR) requirements to all their main suppliers of materials in 2021. The result of this is a thorough evaluation of all main suppliers regarding employment and human rights, health and safety, environment and business ethics. Who Risen considers as their main suppliers has not been directly confirmed by the company. The screening did not find any use of forced labour in its supply chain [92].

6.2.2 Future supply chain

Risen Energy has implemented several plans to expand their production capacity. They plan to increase their cell and module capacity from 22.1 GW to 44 and 39 GW, respectively. This expansion will mainly be accomplished by upgrading their current production locations [93], but also by establishing a new production facility in Inner Mongolia. This facility is one of many similar PV projects in the region, and will include the whole supply chain, from quarts extraction and silicon purification to cell and module production [97]. The total amount of projected new production is shown in Table 6.2.

The company estimates that it will produce 200 000 tons of silicon, 150 000 tons of SoG-Si, 10 GW of wafers and cells and 3 GW of modules. Risen will also build 5.1 GW of combined solar and wind power production to power their PV manufacturing [93]. It is however still unclear as to how much of the total energy need of the production facilities will be met by renewable energy sources. It is also unclear as to how this will affect their current supply chain of wafers and silicon.

6.3 Hanwha Qcells

Hanwha Qcells (Qcells) is the PV branch of the South Korean business conglomerate Hanwha Group. The company was originally a German company, Qcells, founded in 1999. It was acquired by Hanwha after declaring bankruptcy in 2012 [98]. Since its new launch as part of the Hanwha Group, Qcells has grown to be one of the ten biggest PV module manufacturers in the world and is regularly listed as a tier 1 manufacturer by the BloombergNEF methodology [99, 100].

Qcells independently manufacture cells and modules, while the remainder of the supply chain is sourced from other companies. The cell and module production is located in four countries with six manufacturing locations. This is compiled by two locations in China, one in Malaysia, two in South Korea and one in the US [101, 102]. The production capacity of the different plants is shown in Table 6.3. It is evident from the table that while the company is based in South Korea it still has the majority of the production in China, similarly to the other major PV module manufacturers. From Table 6.3 it is also evident there are some gaps of information about the location of Qcells cell production capacity.

Table 6.3: Hanwha Qcells' installed capacity, both current and projected.

Location	**Cells [GW]**	**Modules [GW]**	**Projected Cells [GW]**	**Projected Modules [GW]**	**Sources**
North Chungcheong, KR	4.5	4.5	0.9	0	[78, 103]
Cyberjaya, MY	-	1.1	0	0	[104]
Jiangsu, CN	-	5.1	0	0	[105]
Georgia, US	-	1.7	3.3	6.7	[78]
Total	12.4	12.4	4.2	6.7	[98, 106]

Qcells fronts a very sustainable company mission. The company website and several press releases focus heavily on their different sustainable practises such as their use of hydro power in the supply chain, their transparency and their plans to establish a fully US-based supply chain. The company also fronts them acquiring both the French and the South Korean CFP certification [107].

A Qcells module that has achieved the French Certisolis CFP certification is the Q.PEAK DUO L-G6 425 Wp. It is made through a project specific partnership with Norwegian ingot and wafer manufacturer NorSun, which creates low carbon products. This supply partnership was among the reasons the Qcells module achieved emissions of only 386 kg CO_2-eq/kWp [107].

6.3.1 Supply chain

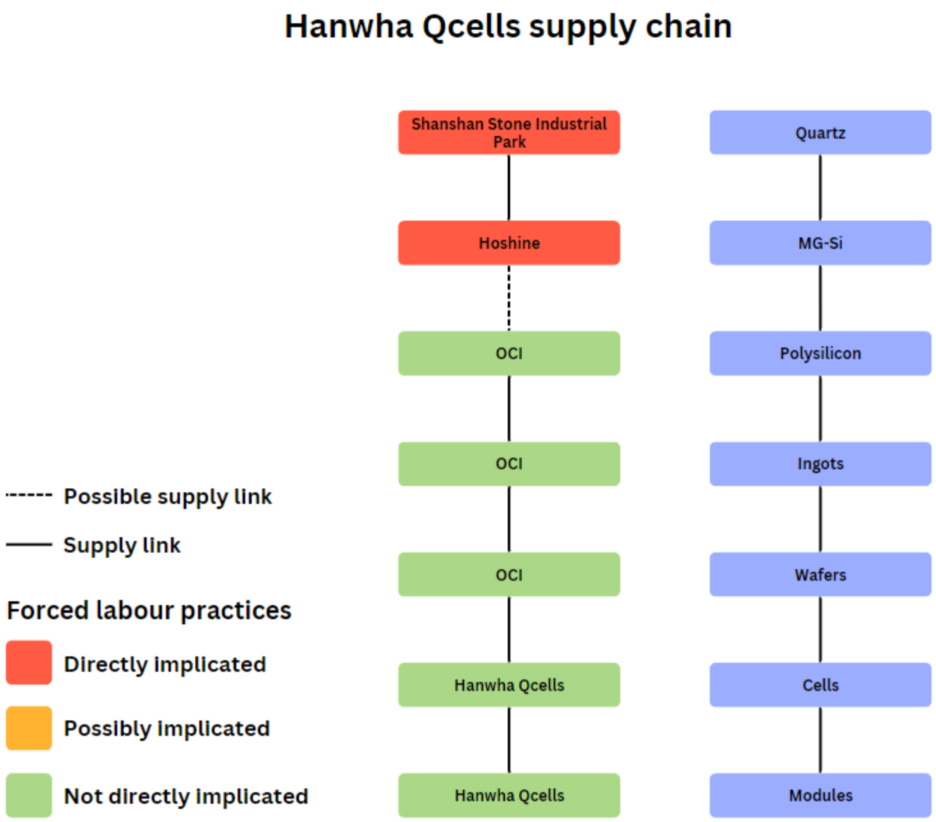


Figure 6.3: The supply chain of Qcells modules.

The steps preceding the cell manufacturing in Qcells supply chain is, as stated previously, completed by other companies. Which companies are presented in Figure 6.3. The manufacturing of polysilicon, ingots and wafers is seemingly mainly outsourced to the South Korean silicon manufacturer OCI. Qcells has current and future supply contracts with OCIMSB, OCIs Malaysian silicon plant. The plant is run on 100% hydro power, which is stipulated as a criteria in the supply contract, and is in line with Qcells' ambitions of low carbon PV production [108]. Evidence of other polysilicon suppliers has not been found.

Following the supply chain further upstream, the available information decreases substantially. The only MG-Si supplier that is implied connected to OCI is Hoshine. The connection between the supplier and the buyer is however, very weak. The only available information on the cooperation between OCI and Hoshine is one post on Hoshine's online investor forum where Hoshine indicated OCI was one of their overseas customers [60].

As described in Section 5.1.1, Hoshine reports outsourcing the raw material extraction to companies within the Shanshan Stone Industrial Park in Xinjiang. The extraction of raw materials completes the PV supply chain, and the total supply chain is illustrated in Figure 6.3.

6.3.2 Future supply chain

Hanwha Qcells has announced ambitions to decrease the environmental impact of their panels. A fundamental aspect of this is in the plans to establish a complete supply chain within the US. Qcells already has a production capacity of 1.7 GW of finished modules at their manufacturing plant in Dalton, Georgia, in the US. In 2022, Qcells announced they would be building a new plant next to the existing one, increasing the capacity in Dalton by 1.4 GW. This year, Qcells has announced a further expansion in Dalton with 2 GW capacity [78].

Qcells established the plant in Dalton in 2019, but it was after the 2022 implementation of the IRA bill the new expansions were announced. In addition to the Dalton plant expansions, the company expressed plans to build a manufacturing plant to produce solar ingots, wafers, cells and finished modules. The plant will have a production capacity of 3.3 GW of all products respectively, and will be situated in Bartow County, Georgia. This would bring the total module capacity in the US to 8.4 GW, and significantly contribute to Qcells aspirations of a complete US based supply chain. The addition of ingot and wafer production in the US would also increase the degree of vertical integration in Qcells' production [78].

To complete the fully US based supply chain, Hanwha Solutions acquired a 21.34% share of polysilicon producer REC Silicon in 2022. REC Silicon has their manufacturing plant located in Moses Lake, Washington. The plant utilises 100% hydro power in their production, as well as the less energy intensive FBR technology in the polysilicon production. This ensures Qcells' access to low carbon polysilicon from REC Silicon. However, the plant has not yet commenced production after closing the plant during the pandemic [109].

REC Silicon sources its MG-Si from several locations, including the US, Norway, Brazil and Australia, according to a representative of the company, N. Kjerstad. One known supplier is the company Ferroglobe [110]. Ferroglobe claims to be the largest merchant producer of silicon metals in the western hemisphere and has both quartz mines and metallurgical silicon plants [54]. Several are located in the US and in Canada, making it possible for Qcells to acquire all or parts of the required polysilicon solely through North American companies.

While Qcells is majorly expanding their production in the US, there has only been one announced expansion in the other production countries. The factory in South Korea is planned to increase its production capacity from 4.5 to 5.4 GW during 2023 [78]. The plants in China and Malaysia have no planned expansions as of yet.

7 Life Cycle Assessment

A life cycle assessment (LCA) is a widely used method of assessing the impacts of a product, process or service, particularly environmental impact [111]. The LCA is a thorough assessment method, and is therefore chosen for this thesis as the tool used to examine the supply chains of the PV modules. Conducting LCAs is commonplace in many industries, but due to trade secrets and competition in the industry, the LCAs are often private.

An LCA is based on a life cycle inventory (LCI). This is collection of every input and output from all processes included in the system being assessed. After gathering an LCI, a chosen LCA program is used to calculate impact. This thesis bases its calculations on the LCA program Simapro. These calculations are to be performed according to different methods. The methods are developed by different companies to be used for LCAs and commonly differ in the weighting of different impacts. The impacts are the direct results of an LCA and are divided into different categories, dependent on what the LCA focuses on. Examples of impact categories can be climate change, human toxicity and resource depletion [111, 112].

LCAs can be divided into different types such as an environmental LCA (E-LCA) or a social LCA (S-LCA). The E-LCA is centred around the environmental impacts of the assessed system. The LCI for an E-LCA is often specific, and numeric data can be gathered directly from manufacturers or indirectly from external sources or previous E-LCAs. An S-LCA assesses the social impacts the system has on possible stakeholders. This may include workers, consumers or local communities. Commonly through interviews, surveys and news sources, the S-LCA considers issues such as working conditions, human rights violations and workplace safety [113, 114].

7.1 Goal

The motivation behind this LCA is its use as guidance for Aneo's future operations in ensuring as high a level of sustainability as possible. The LCA is to be considered a decisional LCA, meaning the results presented in this article may work as guidelines in future selection of products, suppliers and projects. The results may also work towards improving Aneo's knowledge on the industry and their own operations, relating to sustainability.

7.1.1 Target audience

As the research presented in this thesis is performed at the request of Aneo, they will serve as the main target audience. Accordingly, many of the areas of research chosen in this thesis has been guided by the informational needs of Aneo, and the thesis will therefore be catered to their specific need. However, the findings presented will have the possibility of benefiting other companies in the solar industry wishing to improve their practice by taking more sustainable choices. As such, the extended target audience of the thesis is all companies involved in the solar industry seeking to improve their choice of suppliers. While the results of the thesis might not directly be of use, the methodology utilised may guide companies wanting to research their own supply chains.

7.1.2 Intended use of result

Many companies in the solar industry wishes to map the social and environmental impact from the photovoltaic industry. For Aneo, it is important to be a sustainable industry operator, and the results of this report will be a tool to assess its supply chain and create possible demands for its supplier. The goal is to highlight impact hotspots both in the social and environmental impact, and provide Aneo with a comparative report to assist in decision making. Since this study focuses several of the main suppliers of PV modules, and Aneo is only one of many companies buying modules, it is not likely that this report will lead to changes in supply structure. However, the growing concern about social impact in the Chinese PV industry and a large increase in reports related to this issue may contribute to an overall change in the EU solar industry regulations.

7.2 Scope

The scope of this LCA was established according to the requirements posed in the ISO14040 and ISO14044 standards [111, 112]. The LCA will aim to analyse the impact of three PV modules produced by different companies, relating to both social and environmental impacts. The modules analysed are all monocrystalline and from tier 1 companies.

This LCA is performed to analyse a general module from the companies JA Solar, Risen Energy and Hanwha Qcells. Since the electricity mix is calculated based on production capacity in different regions, the end result is not representative for one specific region, but instead for the average production of that specific panel. Because of this, the actual CFP from a specific panel from any of the regarded companies, may differ from that of this assessment. The details regarding method will be further explained in Section 8.

7.2.1 System boundary

When analysing the different modules, a cradle-to-gate system boundary was chosen. This system boundary incorporates all processes from extracting the raw materials to the construction of the modules, i.e. the complete chain of production. The system boundary cut-off is therefore before the modules' period of use and end-of-life disposal. This system boundary was chosen to suit the goal of the study. As the LCA is aimed to help companies choose sustainable modules, the use and end-of-life periods are therefore less relevant for this specific purpose.

This LCA will only focus on the module itself, and will not include other components needed for producing electricity with a PV module. This may include wiring, inverters, mounting systems and more. These components are called the balance of system (BOS). The choice to focus solely on module production and not the BOS was made in collaboration with Aneo to suit the needs of their company.

7.2.2 Functional unit

To adequately compare the chosen modules, the functional unit used in the assessment is 1 kWp of installed capacity of the PV module. As the functional unit relates to possible power production, not the area measured in m^2, modules of different sizes can be easily compared. The functional unit of kWp is one of the recommended functional units from the IEA's methodology for conducting an LCA for a PV system [115]. Using this functional unit ensures the LCA is easily comparable with other higher level LCAs conducted on the same topic. The reference flow for all four modules is the flow of products starting at the raw material extraction and ending at a finished module.

While the functional unit in the LCA is 1 kWp, Simapro is not able to use power units such as kWp or kW as a functional unit. The final results in the Simapro simulation are therefore simulated with a functional unit of kWh. Through the final process, the specific amount of square meters of each panel is chosen as the input, and the wattage of the panel as the output. While the functional unit is different, the calculations in this process would not differ from calculations providing the results in kWp, and the difference of having the Simapro functional unit as kWh is therefore arbitrary.

7.2.3 Method, libraries and impact categories

The inputs available in Simapro depends on which libraries of inputs one imports in the program. When assessing PV modules, a common group of libraries is the Ecoinvent libraries. These libraries are the ones used in the IEA's LCI. For this thesis the following libraries were used:

- Ecoinvent 3 - allocation at point of substitution - system
- Ecoinvent 3 - allocation, cut-off by classification - system
- Ecoinvent 3 - consequential - system
- Method

To interpret the LCI entered into Simapro one needs to chose a method as well as determine which impact categories to measure the modules' impact in. The different methods are imported through the Methods library presented above. As this LCA specifically focuses on carbon emissions and global warming potential (GWP), the method IPCC 2013 GWP 100a was chosen. This method was developed by the Intergovernmental Panel on Climate Change. It analyses climate change factors within a time frame of 100 years. The endpoint impact category of this method is GWP and the impact indicator is kg CO_2-eq. This means the method strictly focuses on assessing the impact based on GWP and measures the results in kg CO_2-eq.

7.2.4 Data quality requirements

For the LCIs of the modules, the base layer of data is provided by the IEA's LCI for PV systems [116]. The report contains a detailed LCI for all main processes in the PV module chain of production. This includes material use, direct emissions, transport and energy use for each process, where the report also includes differences by country.

With the report from IEA as an information base layer, the LCIs for each module will consist of this data with modifications based on research done on the modules' chain of production. To make these modifications, the new information and its source is heavily scrutinised. The sources have been deemed to be credible and recognised by the industry.

7.3 Limitations of the study

It is important to specify that this LCA is a simplified model of the actual system. It is probable that the actual systems contain more differences than what this LCA reflects. Since this LCA is based on literary analysis and not raw data from production sites or manufacturers, there are certain factors that may lead to uncertainties in the result.

The solar market is one of the world's fastest growing industries. This creates the possibility of many developments taking place over the course of a year. The inputs from the general

LCI is based on inputs and outputs from 2018 and some from 2011. Even though the general manufacturing of a module looks the same, it is probable that factors like material efficiency, integrated vertical production and energy efficiency has changed since 2018. To perform a more accurate LCA, the data would have to be gathered directly from the producers, which is not publicly available. This is likely part of the reason that most companies that perform their own third party supported LCA get better results than the general LCA performed without their cooperation.

Conducting research within a competitive industry, such as the solar industry, causes several complications. A main issue, especially prominent when conducting LCAs, is information being classified due to trade secrets. This causes the aggregated data to be less precise and often consist of averages from the relevant market segment. In addition to some data being inaccessible, the data given by the companies themselves might not be reliable. It is not uncommon in industry to embellish the figures to improve the image of the company. Companies also choose to hide certain information for the same reasons. When considering the PV supply chain, a piece of information companies may chose to hide is their involvement in the use of forced labour. In this thesis, many sources used in the literature review express their choice of trusting the self published reports and figures by the companies they research. As such, the results of this thesis may be influenced by incorrect information conveyed by the companies themselves or by secondary sources.

When regarding secondary sources, one can assume the reliability of the data decreases with the amount of links between this thesis and the primary source. This is due to sources paraphrasing, interpreting and prioritising information according to their goals, and thereby risking changing the intended interpretation of the data by the primary source. Due to limitations in budget, contacts and manpower, this thesis will mostly rely on secondary sources. To counteract any alterations to the data, the thesis will be thoroughly cited, enabling readers to easily confirm information from sources closer to the primary source.

8 Life Cycle Inventory

The LCI is the basis for performing an LCA. An LCI is a collection of tables that shows the input and output for a collection of processes. It shows specific material input, electricity demand and source, as well as subsequent outputs and emission related to the different life stages of a product. In this section, the foundational LCI for this LCA will be presented, followed by specific changes in the LCI for the different companies. Assumptions and simplifications done to most accurately depict the specific production methods is also included in the LCI.

8.1 The IEA's general LCI

The LCI used as a general structure for this LCA is published by the IEA Task 12 program, which aims to set guidelines to "Quantify the environmental profile of PV in comparison to other energy technologies" [116]. This LCI is updated in 2018, with some inputs from 2011 and is a collaboration between several countries to standardise the LCI for different PV technologies. The LCI contains information about different production locations such as China (CN), the Asia-Pacific region (APAC), the US (US), Europe without Switzerland (RER) and in one stage of production, Norway (NO). The LCI is comprised of six processes from the refining of quartz sand to MG-Si to the end process of creating the finished module. Each of these processes create a product that is then fed into the next process. For the resulting products of the processes, the amount of product created in process A is not necessarily the amount fed into process B.

The LCI contains inputs for polycrystalline, monocrystalline and perovskite PV modules. It also contains processes for producing the mounting system and recycling the panels. As this LCA focuses solely on monocrystalline modules with a scope of cradle to gate, only the processes for the production of monocrystalline modules will be utilised. Regarding different production methods, the LCI contains the Siemens process for creating polysilicon and the Czochralski method for forming the ingots.

When gathering data to calculate the impact of the module, the LCI from the IEA has provided the base layer of information. As explained in Section 7.2.4, when discovering a piece of information from a credible source that would discern the LCI of one module from the LCI of another, the LCI has been altered. However, to restrict the necessary level of research, only the silicon supply chain has been researched. Other materials used in a module like glass, wiring and coating are included as presented by IEA. As such, the supply chains this thesis will be presenting and discussing is the silicon supply chains. In addition to simplification, the choice of focusing on silicon is due to silicon production being the main contributor of emissions in the total production.

8.1.1 Assumptions

To form the three LCIs for JA Solar, Risen and Qcells, changes has been made to the IEA's LCI, wherever possible. Based on research done on the different companies' production, alterations to the LCI has been collected and then input into Simapro to create the three different LCIs. The specific changes and reasoning behind them will be presented for each company. However, there are some changes to the IEA's LCI that is general for all three companies. These changes are made on the basis of general assumptions.

One general assumption made for all three LCIs is to exclude the transport of products. This assumption was made to simplify the LCI, mainly due to lack of information on the location of manufacturing sites. While some manufacturing sites were easily located, others were not. For example is the complete list of manufacturing sites belonging to Daqo, a supplier of Risen and JA Solar, not publicly available. This makes the assessment of transport distances for polysilicon in two out of three supply chains very uncertain and imprecise. This lack of knowledge on transport distances can be found in several steps throughout all three supply chains. Therefore, it was chosen to neglect transport all together.

Due to Simapro's limited library of regional electricity mixes as well as source specific electricity, some assumptions has been taken regarding the electricity inputs. The electricity inputs are from 2019, and some change in the electricity mix may have occurred. All three simulations has had to create its own electricity mix for one or more processes in the supply chain. These mixes are further specified in the company specific assumptions in Section 8.2.1, 8.3.1 and 8.4.1. A general assumption regarding the electricity mixes concerns transforming high voltage electricity into medium voltage electricity.

In the IEA's LCI all electricity inputs are medium voltage, meaning from 1 kV to 24 kV. However, all electricity inputs from a specific power source, such as a hydro power plant, or from a region within a country, such as a Chinese province, is in Simapro categorised as high voltage, meaning above 24 kV. Medium voltage electricity will have a higher carbon footprint than high voltage. This is partly due to electricity loss during the transformation from high to medium voltage. Subsequently, if using high voltage electricity mixes instead of medium voltage, the total carbon footprint of the modules would be too low. To correct this, it is important to account for the electricity loss in the transformation. This loss is commonly calculated to between 1 and 2% [117]. Therefore, an additional 1.5% of the original electricity input is added to the LCIs whenever a high voltage electricity input is used.

The final general assumption made for this LCA, concerns the use of half-cut cells in the chosen modules. As most new modules entering the market today has half-cut cells, all three chosen modules uses this half-cell technology. However, there are no numbers available in the IEA's LCI regarding the difference in inputs for a regular cell module and a half-cell module. As further research did not yield specific knowledge on the input difference between the technologies, the choice to use LCI inputs for regular cell modules to assess half-cell modules was made. The difference in impact this has regarding the results is assumed to be outweighed by the importance of using high efficiency, modern modules.

8.2 JA Solar

The specific JA Solar module used in this LCA is called JAM72S30 525-550/MR/1500V. It is a monocrystalline half-cell module that has a voltage of 1500 VDC and a wattage of 550 W. The proportions of the module is 2279 mm x 1134 mm. The rest of the specifications for the module is found in the data sheet, in Appendix A. This specific module was chosen by Aneo, as this is a module they have used and may plan to use in the future.

The LCA done for JA Solar uses the IEA's LCI. The whole production chain is based in China with the exception of a minority of the cell and modules manufacturing, which is based in Vietnam and Malaysia. The cell and module manufacturing is done by JA Solar themselves, while the rest of the processes are performed by upstream suppliers. The suppliers has manufacturing plants all over China, and it is therefore not possible to specify where the materials that JA Solar buys comes from. As such, the CN inputs from the general LCI are used in all processes before cell manufacturing. The inputs are the exact inputs found in Table 6, 7, 9 and 13 in the LCI.

Due to cell and module manufacturing being dispersed across three different countries, the electricity mix in the cell and module process is not completely Chinese. The electricity mix used in the cell and module process is calculated by estimating how much of the total manufacturing is done in the different provinces and countries. These estimates are then added to the electricity for that region as a percentage of the total electricity mix, as shown in Table 8.1. The capacity data on cells and modules are gathered from Table 6.1. All the inputs for the cell and module process is found in the IEA's LCI CN Table 16 and 19, with the electricity changed as described above.

Table 8.1: JA Solar's cell and module capacity, and its percentage of the electricity mix.

Location	**Cells [GW]**	**Modules [GW]**	**Cells [%]**	**Modules [%]**
Hebei, CN	6	1.5	21.4	4.1
Anhui, CN	3	3	10.7	8.1
Shanghai CN	-	3	0	8.1
Zhejiang, CN	5	10	17.9	27
Yunnan, CN	5	10	17.9	27
Bac giang, VN	1.5	3.5	5.4	9.5
Penang, MY	1.5	-	5.4	0
Jiangsu, CN	6	6	21.4	16.2
Total	28	37	100	100

A regional grid mix was available in Simapro for all the Chinese provinces JA manufactures in. This was not the case for the manufacturing in Vietnam and Malaysia, and a national grid mix is therefore used for these inputs. The Regional grid mixes from China are high voltage, and a transformation loss of 1.5% has therefore been added to represent the transformation to medium voltage. The Table 8.1 above shows how much each location contribute to the electricity mix.

Table 8.2: The alterations made to the general LCI to create the JA Solar LCI.

Cell						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	CN	17.7	Electricity, high voltage, production mix	CN-AH	1.92*
				Electricity, high voltage, production mix	CN-HB	3.84*
				Electricity, high voltage, production mix	CN-JS	3.84*
				Electricity, high voltage, production mix	CN-SH	3.22*
				Electricity, high voltage, production mix	CN-YN	3.22*
				Electricity, high voltage, production mix	CN-ZJ	0.96
				Electricity, medium voltage. at grid	VN	0.96
Module						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	CN	14	Electricity, high voltage, production mix	CN-AH	1.46*
				Electricity, high voltage, production mix	CN-HB	0.58*
				Electricity, high voltage, production mix	CN-JS	2.30*
				Electricity, high voltage, production mix	CN-SH	1.16*
				Electricity, high voltage, production mix	CN-YN	3.84*
				Electricity, high voltage, production mix	CN-ZJ	3.84*
				Electricity, medium voltage. at grid	VN	1.33
Comments	*High voltage inputs are increased by 1.5% to accommodate losses.					

Table 8.2 shows the inputs that has been changed from the IEA's LCI. The original inputs shows how much electricity from the Chinese national grid mix is needed to make one square meter of each component. The altered inputs has the same total electricity but divided into the regional and national grid mix where the manufacturing bases are located.

8.2.1 Assumptions

As previously mentioned JA Solar only controls the cell and module manufacturing. Before the cell manufacturing process, the materials are supplied by upstream companies. Since there is no information about the regional origin of the specific materials JA buys, the assumption is that all processes prior to the cell process uses the general power mix in China.

The second assumption for JA is in the collection of information. JA has no available, public information regarding the capacity of their manufacturing plants. The company has released the location of the plants, but not the scale of production. Therefore, the data used to alter the LCI is exclusively found through news sites. While the information is not from the primary source, it is assumed the information gathered from various news articles is reliable.

The third assumption is in regards to the electricity mix used in cell and module manufacturing. As previously explained the electricity mix is made up of the regional grid mix in China as well as the national grid mix from Malaysia and Vietnam. It is assumed the manufacturing bases uses these electricity mixes, as opposed to using source specific electricity, such as designated coal or hydro power.

8.3 Risen Energy

Risen produces several different modules for different applications. To make this assessment uniform, a monocrystalline half-cell module from Risen is used for this comparative LCA. The specific module is called HSA RSM110-8-535-560M and has a voltage of 1500 VDC, a wattage of 560 W and an efficiency of 21.4%. The module is 2384 mm x 1096 mm [118]. The remaining module specifications are found in Appendix B.

Risen is currently only responsible for its production of cells and modules, therefore the quartz mining, silicon purification and, ingot and wafering process is the exact same as in the general LCI from the IEA for production in China CN. Risen is supplied by the largest silicon and wafer producers on the market, as shown in Figure 6.2, and it has not been possible to identify their area specific upstream supply chain. Therefore the data is not sufficient to make any specific calculations for Risen's supply chain before the cell production. For these calculations, the specific CN inputs from Table 6, 7, 9 and 12 is used.

Table 8.3: Risen Energy's cell and module capacity, and its percentage of the electricity mix.

Location	Cells [GW]	Modules [GW]	Cells [%]	Modules [%]
Malaysia, MY	3	3	13.57	13.57
Zheijang, Yuwi, CN	5	5	22.62	22.62
Zheijang, Ninghai, CN	4.1	4.1	18.55	18.55
Jiangsu, CN	5	5	22.62	22.62
Anhui, CN	5	5	22.62	22.62
Total	22.1	22.1	100	100

There are two differences between the general LCI from the IEA and the Risen Energy LCI. First and foremost is the differentiated and more complex electricity mix used in the calculations. Risen has no reported use of dedicated coal power at their production site, so a grid based electricity mix from the different production sites is the basis of this assessment. To calculate this, the percentage of production at each individual region compared to total production has been calculated, as shown in Table 8.3. This electricity mix is then put into Simapro and used in the cell and modules production. Since the electricity mix for specific regions in China is only available as high voltage in the Ecoinvent database, a transformation loss of 1.5% has been added to the electricity demand in the Chinese regions. For Malaysia, medium voltage electricity was available, and therefore has no transformation loss. The changes were done in Table 16 and 19 of the general LCI, and the rest of the CN inputs remain the same as the IEA's LCI.

The other difference is the use of new frame technology. Risen claims to utilise a steel frame in their new modules. Therefore, the aluminium alloy (AlMg3) input in Table 19 of the IEA's LCI is changed to steel low-alloyed in the Simapro calculations.

Table 8.4: The alterations made to the general LCI to create the Risen Energy LCI.

Cell						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	CN	17.7	Electricity, high voltage, production mix	CN-AH	4.00*
				Electricity, high voltage, production mix	CN-JS	4.00*
				Electricity, high voltage, production mix	CN-ZJ	7.29*
				Electricity, medium voltage. at grid	MY	2.40
Module						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	CN	14	Electricity, high voltage, production mix	CN-AH	3.21*
				Electricity, high voltage, production mix	CN-JS	3.21*
				Electricity, high voltage, production mix	CN-ZJ	5.85*
				Electricity, medium voltage. at grid	MY	1.90
kg	Aluminium alloy, AlMg3, at plant	RER	2.13	Steel, low-alloyed	GLO	2.13
Comments	*High voltage inputs are increased by 1.5% to accommodate losses.					

Table 8.4 shows the direct changes made in the input for the Simapro calculation for Risen Energy. The table shows the original input from IEA's LCI and the input that has replaced it.

8.3.1 Assumptions

The first assumption for Risen Energy is in the supply chain. It is assumed that the upstream supply chain before production of cells and modules is located various places in China. As there is no available data on where the upstream supply chain manufacturing is located, with regards to specific Chinese regions, it is not possible to use a regional specific electricity mix. For these production stages, the general power mix in China is utilised.

The next assumption is done to simulate the electricity mix in cell and module production. It is assumed that Risen utilises the regional electricity mix in their production, instead of external private energy sources such as coal plants or solar panels. It may be that some of the production sites have inputs from dedicated power sources such as solar or coal plants, but since it is uncertain, the regional electricity mixes is used in the assessment.

The final assumption that has been done is the input of steel instead of aluminium in the frame. Steel is 4.5 times less polluting on a weight basis than the regular aluminium frame. Even though this is not necessarily included in all modules, in this LCA, it is assumed that this frame is used in all module production. This is based on the assumption that Risen energy will likely want to utilise this new frame as rapidly as possible. The precise input of this new frame is not publicly available. It is possible that the weight of the steel frame is somewhat higher than that of the aluminium frame because of higher material density, but it could also be that less steel than aluminium was required, since steel is more sturdy. What type of steel alloy they use is not public information either. Therefore, since it has not been possible to determine the precise weight or input, it is assumed that input of steel is the same weight as input of aluminium, and a low alloyed steel has been chosen.

8.4 Hanwha Qcells

The chosen Qcells module used in this LCA is the Q.PEAK DUO ML-G11S+, a monocrystalline half-cell module. It has a voltage of 1500 VDC and a wattage of 510 W. The proportions of the module is 2092 mm x 1134 mm. Other specifications is found in the data sheet, in Appendix C. This module was the Qcells module most similar to the JA Solar module used by Aneo.

As Qcells' upstream suppliers are situated in various countries in Asia, some stages of the processes created in Simapro will largely follow the China based LCI inputs (CN) of the IEA's LCI while others follow the APAC inputs (APAC). In the processes, the main change made from the general LCI is the utilised electricity mixes.

The extraction of quartz and manufacturing of MG-Si in Simapro strictly follows the CN inputs of Table 6 of the IEA's LCI, with no input changes other than the non-inclusion of transport and disposal. The production of polysilicon by OCI is situated in Malaysia, and the simulated process therefore uses the APAC inputs in the IEA's LCI Table 7. Here, the utilised electricity is changed from a medium voltage grid mix from South Korea to high voltage Malaysian hydro power, with an added 1.5% of used electricity to account for loss.

The ingot and wafer production is both situated in Malaysia and performed by OCI. Accordingly, the simulated processes both utilise the APAC inputs from Table 9 and Table 13 of the IEA's LCI, respectively. Similarly to the previous step, the electricity used is high voltage Malaysian hydro power with an electricity loss in the transformation.

For the production of cells and modules, the IEA's LCI inputs are exactly the same for the CN, APAC and US inventory, except for the origin of the inputs. As there is no numerical difference for the different regions, Qcells' LCI follows the IEA's LCI inputs in Table 16 (CN) for cell production and Table 19 (CN) for module production, despite Qcells' actual production being geographically dispersed. The only changes made to the inputs is the electricity mix.

Table 8.5: Hanwha Qcells's cell and module capacity, and its percentage of the electricity mix.

Location	**Cells [GW]**	**Modules [GW]**	**Cells [%]**	**Modules [%]**
North Chungcheong, KR	4.5	4.5	45	36.29
Cyberjaya, MY	1.1*	1.1	11	8.87
Jiangsu, CN	5.1*	5.1	27	41.13
Georgia, US	1.7*	1.7	17	1.7
Total	12.4*	12.4	100	100
Comments	*Assumed numbers without a direct source.			

To complete the inputs from Table 16, 17, 19 and 20, a new electricity mix that reflected the dispersion of manufacturing plants in Qcells' production was needed. This electricity mix is based on Table 8.5. By looking at the dispersion of the production, in a percentage of the total production, an electricity mix could be made by using these percentages of electricity from the different countries and combining them to one mix.

The electricity mix differs from cell to module production. In Table 8.5, some numbers are marked with an asterisk, representing assumed numbers. The assumption behind the numbers will be further explained in Section 8.4.1. For both cells and modules the production in South Korea is input with a national grid mix, the production in Malaysia is input with 100% hydro power and the production in China is input with a regional grid mix for the Jiangsu province.

For the US, Simapro did not have a Georgia specific electricity mix. Due to the severely varying level of fossil fuels used in the different states in the US, a Georgia specific electricity mix was made. This was done by creating a new process in Simapro where the output was 1 kWh of a Georgia grid mix and the input was 0.439 kg of CO_2 emissions. This process was then used as an input in the cell and module electricity mixes. The number of CO_2-eq is taken from the organisation Electricity Maps, which produces live maps presenting the CO_2 emissions of electricity grid mixes in areas all over the world. The specific emission level was found by selecting the Southern Company Services, Inc. region and choosing a period of 12 months to create a level of emission averaged over a year. The specific period selected was from April, 2022 to March, 2023 [119].

The cell specific electricity mix was made with the cell percentages from Table 8.5, and the module specific electricity mix with the module percentages. Both the Chinese and the Malaysian electricity was high voltage, and an additional 1.5% of these inputs were therefore added to represent transformation loss from high to medium voltage.

Table 8.6: The alterations made to the general LCI to create the Hanwha Qcells LCI.

SoG-Si						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	KR	49	Electricity, high voltage, hydro, tropical region	MY	49.74*
Ingot						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	KR	32	Electricity, high voltage, hydro, tropical region	MY	32.48*
Wafer						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	KR	4.76	Electricity, high voltage, hydro, tropical region	MY	4.83*
Cell						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	KR	17.7	Electricity, high voltage, hydro, tropical region	MY	1.59*
				Electricity, high voltage, at grid	CN-JS	7.39*
				Electricity, medium voltage. at grid	KR	6.42
				Electricity, medium voltage, at grid**	US-GA	2.43
Module						
	Original			***Altered***		
Unit	**Input**	**Origin**	**Value**	**Input**	**Origin**	**Value**
kWh	Electricity, medium voltage, at grid	KR	14	Electricity, high voltage, hydro, tropical region	MY	1.26*
				Electricity, high voltage, at grid	CN-JS	5.84*
				Electricity, medium voltage. at grid	KR	5.08
				Electricity, medium voltage, at grid**	US-GA	1.92
Comments	*High voltage inputs are increased by 1.5% to accommodate losses. **The Georgia electricity mix is created specifically for this process.					

All of the changes made to the IEA's LCI to create the Qcells LCI is compiled and presented in Table 8.6. The processes which has been altered begins at the refining of SoG-Si and ends at the module production.

8.4.1 Assumptions

Regarding the supply chain, the first assumption needed to simulate the production of the Qcells module is that all raw material extraction and MG-Si production needed in Qcells' supply takes place in China. The link between OCI and Hoshine described in Section 6.3.1 as well as China holding the largest market share of polysilicon production, as shown in Figure 5.3, is the basis of the assumption.

Another assumption is that OCI is Qcells' only supplier of polysilicon, ingots and wafers. Qcells' general transparency gives credit to this assumption, as they only name OCI as a supplier of these products. Considering Qcells' own cell production of 10 GW, amounting to 30 000 MT of polysilicon, and OCIMBS' capacity of 35 000 MT, it is possible OCI has Qcells as their main customer [120].

Concerning the distribution of production, as shown in Table 8.5, the number of GW of cells produced in Malaysia, China and the US has been assumed due to specific sources for these numbers not being discovered during the research. Firstly, the total cell production capacity has been assumed to 12.4 GW. Sources confirm the cell production capacity to be at least 12 GW in May 2022 [106], and the module production capacity to currently be at 12.4 GW [105, 98]. As the production of cells and modules by a company is often vertically integrated, it is assumed that the current cell production capacity have followed the increase of the module capacity, totalling to 12.4 GW. Continuing with the reasoning of vertical integration at the manufacturing plant, the specific cell production capacity dispersion is assumed to mirror the module production capacity. Meaning the plants produces the same amount of cells as modules.

To create the electricity mix used in the cell and module production, it is assumed that the Chinese manufacturing plant utilises the regional mix as opposed to a national mix or a source specific electricity, such as coal or hydro power. This was also assumed concerning the Georgia, US electricity mix. For Korea, a national grid mix has been assumed, while for the Malaysian manufacture, it is assumed the production continues the use of hydro power.

The Georgia electricity mix created for the LCI depends on several assumptions. Firstly it is assumed that the Dalton, Georgia manufacturing plant utilises the Southern Company Services, Inc. regional grid mix. Secondly, it is assumed an average emissions level based on the period of March, 2022 until April, 2023. This information is more updated than the Simapro electricity inputs, which are based on 2019 data. Lastly, the way the Georgia electricity mix was simulated includes nothing but the CO_2-eq emissions. Due to this, utilising this electricity mix to look at anything other than GWP and CO_2-eq emissions would yield incorrect results.

9 Results

The results presented in this section is obtained from the Simapro software, by entering the LCI data presented in Section 8 and applying the methods presented in Section 7.2.3. The results enables the comparison of the three modules on the basis of total emissions and process differences.

The illustrations of the processes and results in the Simapro networks are presented with the node cut-off set at 2%, meaning only inputs with an emission higher than two percent of the total emissions are shown. In other words, the processes contain more inputs than shown in the networks, but these have been excluded as to make the illustrations easily comprehensible. The results presented in these networks are cumulative. This means the presented emissions from one process contains all emissions from the supply chain leading up to said process.

9.1 Comparative results

Through using the IEA's LCI data it was possible to create Figure 9.1, which shows how much electricity each process needs to create 1 m^2 of a generic PV module. Each square meter of finished module requires 88.6 kWh of electricity throughout the chain of production. The production of SoG-Si has the highest electricity demand with 31% of the total electricity demand. Combined, the cell and module process uses 35% of the total energy demand.

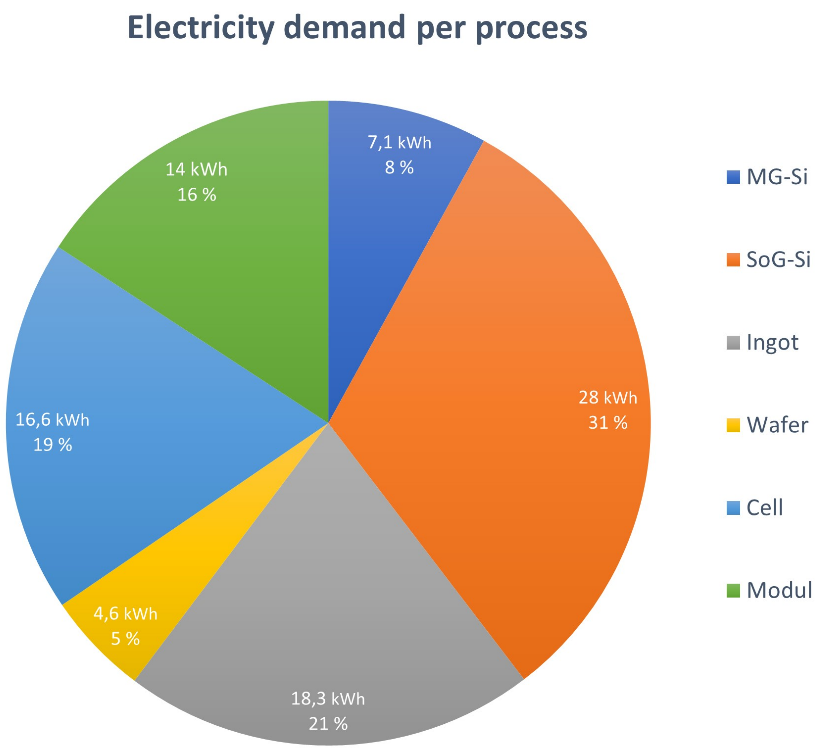


Figure 9.1: The electricity demand per stage of production [kWh/m^2].

The process specific electricity demands presented in Figure 9.1 enables the calculations of the company specific electricity demand to produce 1 kWp of their module. Table 9.1 presents the company specific electricity demand as well as the amount of square meters needed for each module to produce 1 kWp. The modules has different specifications, e.g. wattage and size. However, their m^2/kWp is very similar, as shown in the table. Risen has a slightly more effective module than JA Solar, as it needs less square meters to produce the same wattage. The Qcells module is slightly more effective than the Risen module. This is also shown through the production electricity demand per kWp, where Qcells is the most effective, followed by Risen and JA respectively.

Table 9.1: The required area of module and electricity to produce a kWp, measured respectively in m^2/kWp and kWh/kWp.

Module	[m^2/kWp]	[kWh/kWp]
JA Solar JAM72S30 525-550/MR/1500V	4.699	416.33
Risen Energy HSA RSM110-8-535-560M	4.666	413.41
Hanwha Qcells Q.PEAK DUO ML-G11S+	4.652	412.17

The results in Figure 9.1 and Table 9.1 provide the basis of comparison for the modules, showing the modules' level of similarity. Additionally, through the use of the functional unit of 1 kWp, all inputs and emissions are calculated relative to one commonality.

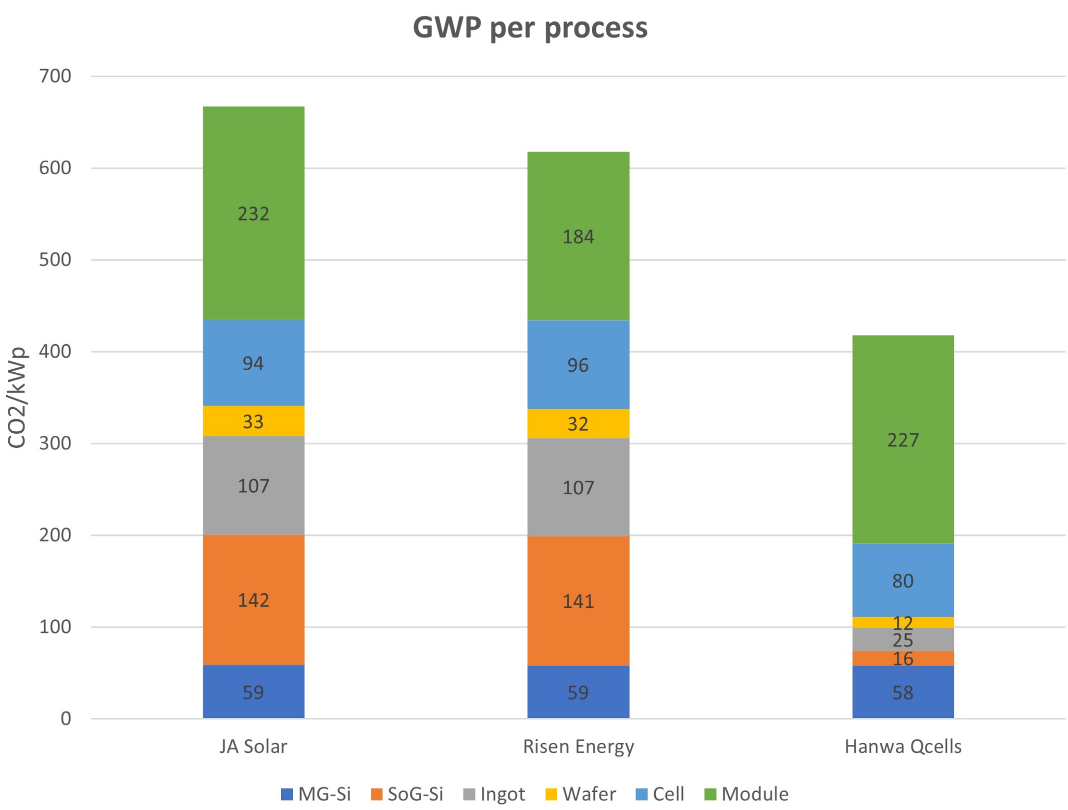


Figure 9.2: The CO_2-eq emissions per process for all three modules.

Figure 9.2 shows the individual emissions from the different manufacturing processes. It is evident that the module manufacturing is the process with the largest emissions. This is mainly because larger components such as solar glass and module frames are included in this process. The total emissions from JA Solar is the largest with Risen Energy following second and Hanwha Qcells' emissions being the lowest. Regarding the emission totals, JA Solar and Risen Energy has the most similar emissions.

Table 9.2: Emissions per process [CO_2-eq/kWp]

Process	**JA Solar**	**Risen Energy**	**Hanwha Qcells**
MG-Si	58.9	58.5	58.4
SoG-Si	142.1	140.5	15.7
Ingot	107	107	24.8
Wafer	33	32	12.1
Cell	94	96	80
Module	232	184	227
Total	667	618	418

From Table 9.2 it is evident that the first process of the chain of production is very similar for all three modules. After this step, the emissions from the modules vary significantly, with the largest difference being in the production of SoG-Si. In this process, Qcells' emissions are approximately 11% of the emissions of JA Solar and Risen. Throughout all processes, with the exception of the module production, Qcells has the lowest emission. In the module production, Risen's emissions is 79% and 81% of that of Qcells and JA Solar, respectively. For JA and Risen, all processes except module manufacturing has almost identical emission levels.

9.2 JA Solar

Figur 9.3 below shows the Simapro LCA network of JA solar's module. The system presented has functional unit of 1 kWp and cut-off set at 2%. The light-green boxes to the left shows all the processes from MG-Si to module. The CO_2-eq emissions presented in the network processes are cumulative, and does not describe the individual emissions for each process. The module has a total emission of 667 kg CO_2-eq/kWp. Electricity is by far the largest contributor with around 402 kg CO_2-eq of the total emissions. The second and third biggest emission contributors comes from the module manufacturing process when adding aluminium frame and solar glass.

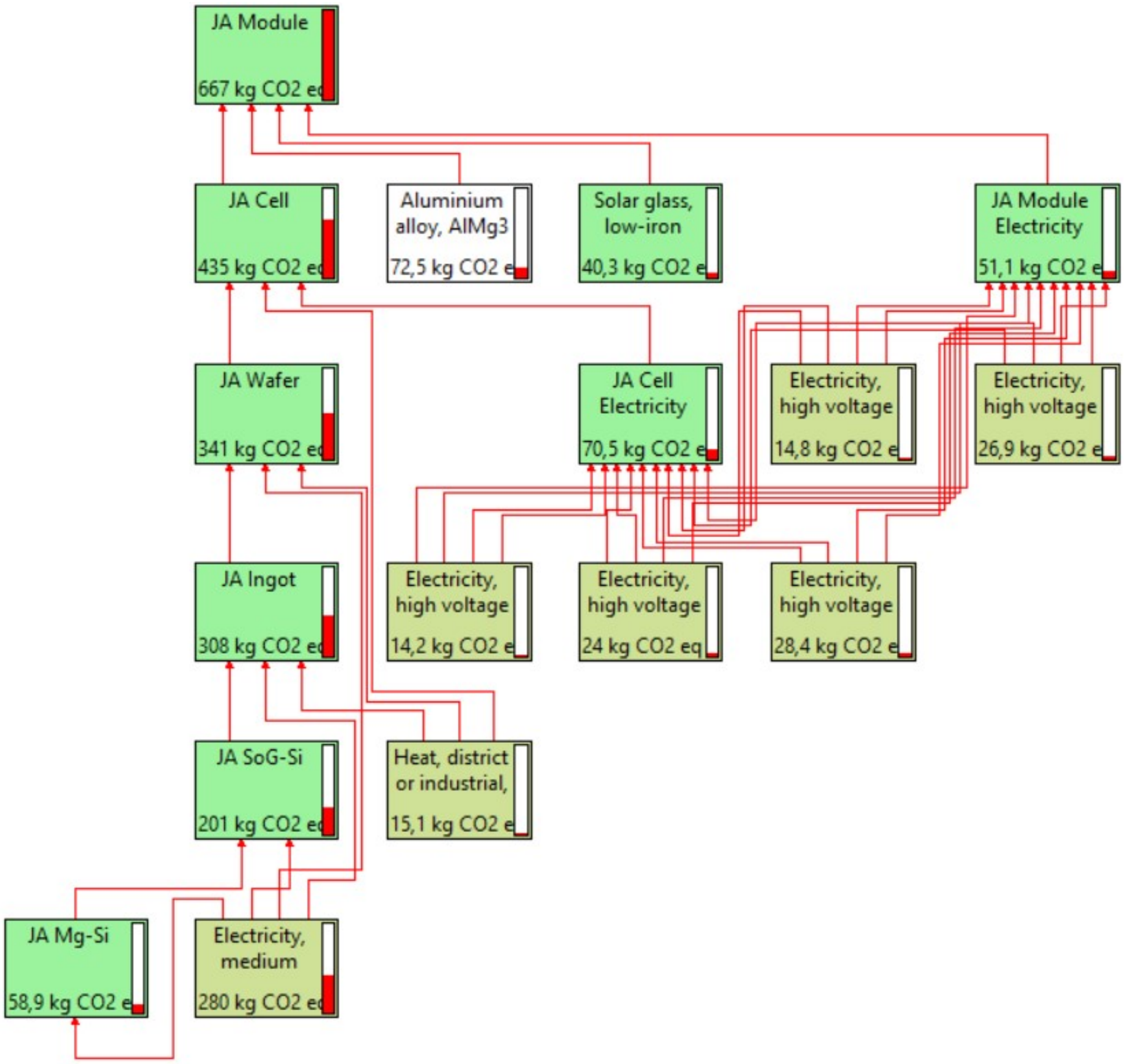


Figure 9.3: The LCA network of JA Solar.

Figure 9.4 shows the largest single input emissions contributors from the whole supply chain to JA Solars module. The national Chinese electricity mix is by far the largest emissions with 280 kg CO_2-eq. This is the electricity mix used in all the processes except cell and module as shown in Figure 9.3. The components added in the module process has the second largest emissions. Aluminium and solar glass has a combined emission of 112.8 kg CO_2-eq. Followed by electricity mix used in the cell and module process. Inputs lower than 2% of the total emission are all represented in the "Remaining processes". This includes smaller electricity contributions, chemicals, and other materials.

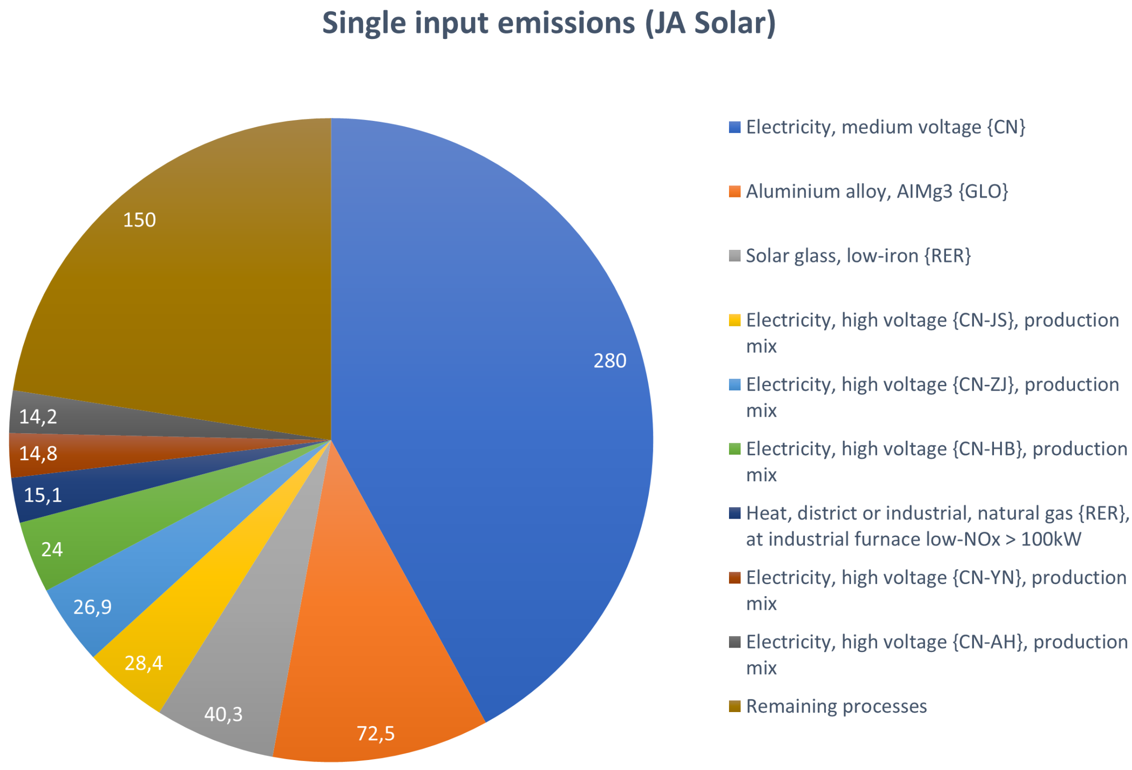


Figure 9.4: The individual inputs with the largest CO_2-eq emissions throughout the whole chain of production [kg CO_2-eq/kWp].

9.3 Risen Energy

Figure 9.5 shows the Simapro network of a Risen Energy module with a 2% cut-off. The calculations is done for the functional unit of 1 kWp. The total sum of CO_2-eq emissions for the functional unit is 618 kg. It is clear from the Simapro network that the main contributor to emissions is from the electricity usage, which accounts for approximately 411 kg CO_2-eq. The emissions from all energy is closer to 426 kg CO_2-eq. After energy, the solar glass and steel frame have the highest emission.

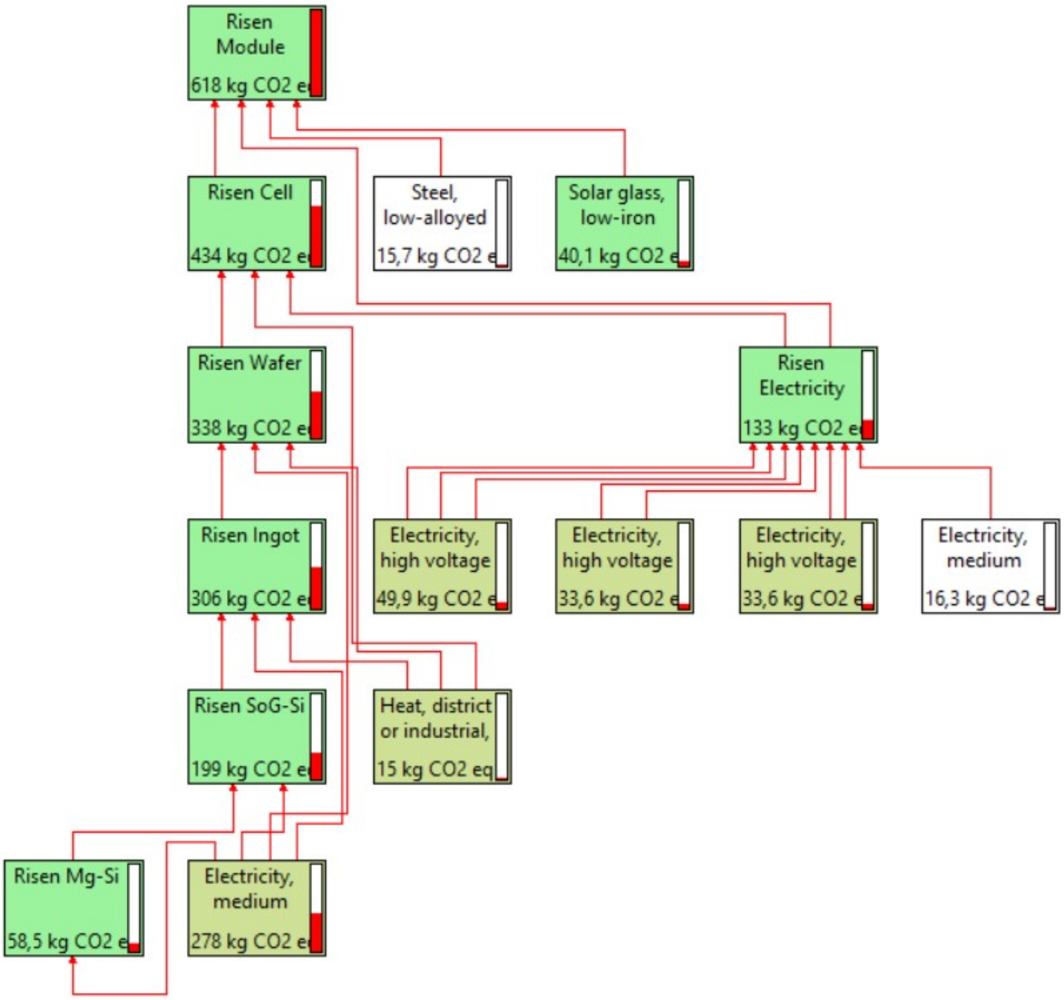


Figure 9.5: The LCA network of LCA of Risen Energy.

Figure 9.6 shows the emissions from the single inputs. This figure also shows that the main emission is from the national Chinese electricity mix, which is used in in the processes from MG-Si purification to the wafer production. The following highest emitters are in the different regional electricity mixes that is used for cell and module manufacturing. Solar glass and low alloyed steel is the biggest non energy related emitting inputs.

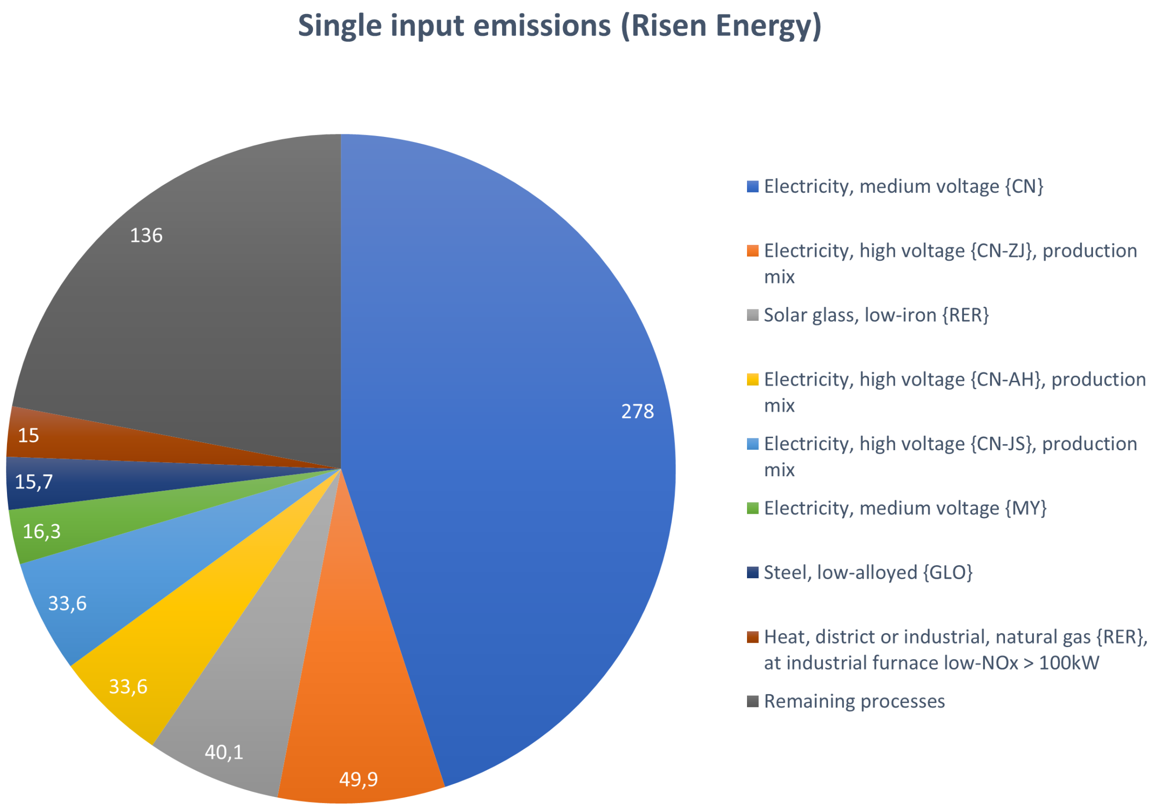


Figure 9.6: The individual inputs with the largest CO_2-eq emissions throughout the whole chain of production [kg CO_2-eq/kWp].

9.4 Hanwha Qcells

The chain of production of Hanwha Qcells' module is presented in Figure 9.7. The network has a 2% cut-off, and uses the functional unit of 1 kWp. For a functional unit, the total emissions add up to 418 kg CO_2-eq/kWp. It is evident from the network that from the MG-Si production until the cell production, electricity and heat are the largest contributors. For the module production, it becomes evident that other inputs, such as the aluminium frame and the glass, has a significant contribution to the final emissions.

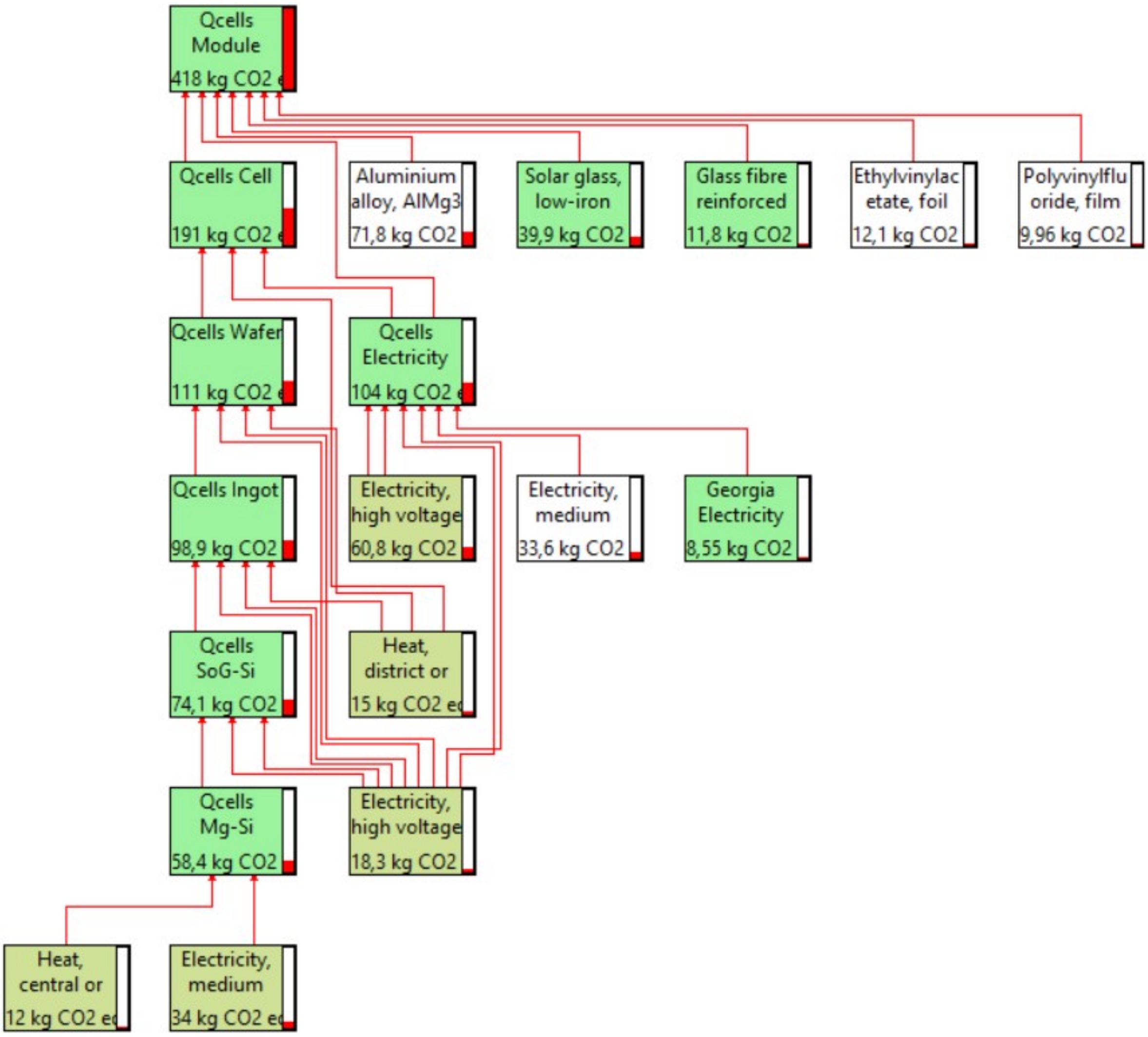


Figure 9.7: The LCA network of LCA of Hanwha Qcells.

The final stage in the production, the module manufacturing, is the dominating process in terms of emissions. This is presented in Table 9.2. Following the module production is the cell process and MG-Si process respectively.

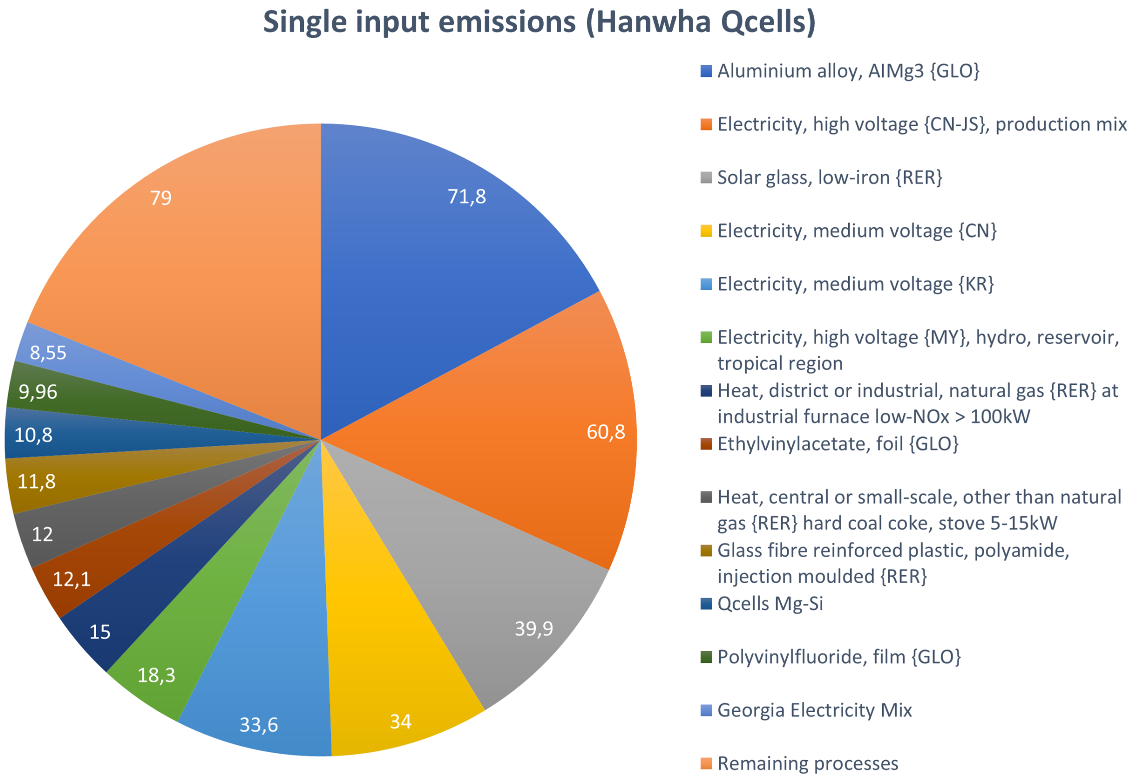


Figure 9.8: The individual inputs with the largest CO_2-eq emissions throughout the whole chain of production [kg CO_2-eq/kWp].

The module components being among the biggest input contributors to the total emissions is clear from Figure 9.8, which presents the inputs with the largest individual CO_2-eq emission. The results shown in Figure 9.8 is also illustrated with a 2% cut-off. The input with the biggest CFP throughout the whole chain of production of the Qcells module is the aluminium alloy used in the module frame. It represents 17.2% of the total CO_2-eq emissions. The glass used in the module is the third largest individual input with 39.9 kg CO_2-eq/kWp.

In Figure 9.8, it is also evident that the energy inputs in the processes are large contributors. Of the 13 inputs contributing more than 2% to the total emissions, five are electricity inputs. The largest of these is the electricity production mix from Jiangsu in China, which is used in the electricity mix for the production of cells and modules.

Table 9.3: Electricity demand in the Qcells production chain, and the subsequent emissions from this electricity use.

Process	**Electricity demand [kWh/kWp]**	**Emissions [kg CO_2/kWp]**
MG-Si	33.03	34.01
SoG-Si	130.26	9.59
Ingot	85.13	6.28
Wafer	21.40	1.57
Cell	77.22	56.29
Module	65.13	47.45
Total	412.17	155.18

In Qcells' chain of production, how energy intensive a process is is not directly linked to how polluting it is. Table 9.3 presents the electricity demand of the different processes in the production chain of the Qcells module, as well as the emissions from said electricity. The electricity demand of the Qcells module is calculated from the general PV production electricity demand per square meter, presented in Figure 9.1, multiplied by the amount of square meters needed to produce 1 kWp, presented in Table 9.1. The emissions from the total amount of electricity necessary to make the Qcells module adds up to 155.18 kg CO_2-eq. While the production of SoG-Si and ingots create the largest electricity demand, these processes have the least emissions, with the exception of wafer production. These three processes are the ones run completely on Malaysian hydro power.

10 Discussion

This thesis is, as mentioned previously, written on behalf of the renewable energy company Aneo, to review current and potential suppliers of solar modules. The main focus has been on the environmental and social impact the different modules have during their production. The results presented in the previous Section 9 has shown the direct GWP potential of each module, and Section 6 has illustrated how the different companies might be indirectly connected to the use of forced labour. In this section, the results and findings of this thesis will be highlighted, compared and discussed. The goal is to present the advantages and disadvantages of the different companies this thesis focuses on.

10.1 Environmental sustainability

Comparing the total emissions from each module, Hanwha Qcells has a distinctly lower level of emissions than the two others. This is largely due to the location of the manufacturing, especially concerning the electricity mixes. Where JA and Risen has close to their entire supply chain located in China, Qcells has several steps in the supply chain located outside of China. The manufacturing of polysilicon, ingots and wafers by OCI in Malaysia is the main source of emission reduction in Qcells' supply chain. As OCI utilises 100% hydro power in their production, the emissions are reduced significantly compared to that of JA's and Risen's supply chain which is mainly located in China. The suppliers of JA and Risen are using local electricity mixes in the regions they are producing in, which are largely coal based. The effect using different electricity mixes has on the total emission of a module, shows the importance of clean energy in the supply chain.

The electricity mixes being a deciding factor for the CFP of a module is made evident by the total electricity based CO_2-eq emissions from the modules. In Sections 9.2, 9.3 and 9.4 electricity based emissions are presented as 401.6 kg CO_2-eq for JA, 411 kg CO_2-eq for Risen and 155.18 kg CO_2-eq for Qcells. It is evident from Table 9.3 that the use of hydro power has strongly influenced the difference in emissions from the modules. No supplier in the modules' supply chains except for OCI is reported to use source specific electricity, either fossil fuel based or renewable. However, some of the suppliers might be affected by the Xinjiang coal power centres.

As presented in Section 4.1, the Xinjiang province contains vast coal resources, and some sources claim the coal power production in the area may be directly feeding local industries, as opposed to using a grid based electricity mix. If this has been the case in the modules' supply chains, it would negatively affect the emission levels of the production. As OCI and Qcells has a specific contract requirement of 100% hydro power used in manufacturing, the majority of Qcells' supply chain would not be affected. However, the supply chains of JA and Risen may be more exposed to the electricity emissions being even larger than calculated in this thesis, due to the possibility of coal power centres in Xinjiang being used in the PV industry.

The level of emissions may also be lower than the results show. This possibility may be due in part to the prevalence of trade secrets in the industry. As companies improve their technology to increase efficiency, reduce cost or increase sustainability, they often want to keep this secret to keep their competitive edge. Such trade secrets make it difficult for outsiders to accurately depict and calculate a products CFP. It is a significant possibility that all three companies have less polluting production chains for their modules, but the changes from the general IEA's LCI needed to show this are not publicly available, which may imply the presence of trade secrets.

The integrated electricity required to produce specific input materials could also affect the results. The most polluting part of the modules after electricity is the aluminium frame. Aluminium is highly energy intensive to make, and a change in the electricity mix for this material would therefore reduce the total emissions. In the LCI, the aluminium used is of global origin. The electricity used in the aluminium production is therefore based on a global average of electricity used in aluminium production. Knowing the origin of the aluminium for the companies' LCI might have noticeably affected the total emissions, especially if the aluminium originates from a country with a renewable energy based electricity mix. This is just one example of how a supply chain utilising less polluting electricity could reduce emissions in more ways than just replacing process specific electricity demand.

10.2 Social sustainability

The exponential market growth of the solar industry has had an undeniable social impact for many labourers in the Uyghur region in China. The increased need for workers, combined with the Chinese governments policies on assimilating the Uyghur people has created an environment fostering forced labour. To restrict and mend the impact this has had on the ethics of the PV industry, a necessary step will likely be import restrictions, such as the strict restrictions on PV modules and components from forced labour exposed companies implemented in the US. The EU has not implemented any restrictions as of yet, but as described in Section 5.2.3, a proposed ban is awaiting processing in the European Parliament. The different restrictions and tariffs that may be levied towards forced labour exposed manufacturers may be critical for the development of social sustainability in the solar industry.

The worlds largest MG-Si and polysilicon suppliers being centred in Xinjiang creates a difficulty concerning implementing bans on modules using forced labour in their supply chain. Companies such as Hoshine and Daqo having proven and alleged use of forced labour puts a majority of PV module manufacturers' supply chain at risk. As these suppliers are such large actors in their markets, it would be almost impossible for module manufacturers to boycott as this leaves a large shortage of polysilicon products in the remaining market. Because of this, pressure from the EU and the US is very important as it coordinates the pressure on the upstream supply chain.

When implementing bans and import restrictions or conducting boycotts, it is important to consider that the social sustainability may differ for different products from the same company. Many of the largest manufacturers in the industry have production locations in Xinjiang, in addition to other provinces. This makes it very possible that only parts of their production is affected by the use of forced labour. Downstream manufacturers, customers and governments will have to evaluate if it is sustainable to buy a product from a supplier utilising forced labour, even if the product bought is guaranteed to not have been made with forced labour. Considering the market share of many of these upstream companies, a total ban on all their products would probably not be feasible while still meeting the increasing demand of PV modules. Focusing a ban on specific products would be easier to implement, but does not have the same significant consequences for suppliers utilising forced labour.

An issue that may arise by only focusing on specific products instead of the supplier is that the company may split their supply chain into streams with different levels of social impact. For example, polysilicon manufacturers could ensure that part of the polysilicon produced is made without forced labour. This polysilicon would then be supplied to the module manufacturers with higher social sustainability standards. Meanwhile, the forced labour produced silicon goes to other markets. In that case the total use of forced labour would not be decreased, just more concentrated. Separated supply chains may be how many companies, such as Risen, can conduct CSR assessments and end up with a clean supply chain even though they both are connected to Hoshine, GCL-Poly and Xinte in their upstream supply chain.

It is important to highlight that a large part of PV manufacturing is not based in Xinjiang and therefore does not utilise forced labour. This exemplifies how forced labour is not necessary to conduct large scale PV production. Because of this, ceasing the use of forced labour would probably not be detrimental to the Chinese or the international PV industry. Thus, international pressure from markets, governments and large institutions such as the EU and the UN could be sufficient to end the of forced labour in the PV industry.

10.3 Choice of module

The modules being manufactured by different suppliers leads to differences in the panels, despite having almost the same installed capacity. However, all three modules use the same technologies; monocrystalline, half-cut cells with the approximately same efficiency. Nevertheless, they will differ from one another in some ways that could lead to an unfair comparison between the modules.

An example of a possible factor leading to an unfair comparison is the module size. When comparing a 1 m^2 module with a 2 m^2 module, the frame is a significantly smaller part of the total module. This is because the frame will be approximately the same width on both modules, and when the square meters doubles the circumference does not. Therefore the increase of module area is larger than the increase of the frame. As such, the frame of bigger modules will have a smaller part of total emissions. While the modules assessed in this thesis is of similar sizes, this will need to be taken into consideration when comparing the results of this thesis with modules of other sizes.

As mentioned in Section 8.1.1, all the modules in this report use half-cut cells, as this is the new standard for monocrystalline modules. Half-cut modules were chosen as they better represent the market standards for efficiency and nominal power. However, the half-cut process is not included in the LCI. This process uses lasers to cut the cells, which consumes electricity. The amount of electricity and added materials needed to use half-cut cells in a square meter of module is unknown. Therefore this process was excluded from the LCA. Since all the modules assessed are half-cut, they will still be comparable with each other. However, this difference need to be taken into account when comparing these results to other modules. It also means that the electricity needed to create a half-cut module will be higher then represented in the result, increasing the total emissions of the module.

Its important to note that the performed LCA's are subject to discrepancies compared to the actual module production from JA, Risen and Qcells. The LCA is produced with the LCI from the IEA as a general structure, and inputs are changed based on available information. Since the LCI is a comprised of data from before 2023, it is likely that the current production has improved. Because of this, the results could be positively biased towards the companies with the most available information.

10.4 JA Solar

JA has the most manufacturing bases of all the companies examined in this thesis, with 12 locations as of 2019. JA has no public record about how much manufacturing capacity each base has. Therefore the data has been collected by many different news articles, who have reported on JA's press releases about their expansions. The news articles usually contains JA Solar's plans for when, where and how large a new manufacturing base is gonna be, but rarely any confirmation regarding when the construction of the base is completed. This can lead to uncertainty in the data collected about capacity in the different regions, leading to an inaccurate final result.

A factor that impacts JA's environmental sustainability, is how geographically dispersed it is within the country. With ten manufacturing bases across six provinces, JA's manufacturing depends on many specific electricity mixes. Thus, the expansion of renewable energy in one specific region will not significantly reduce the emission of JA's module production. With the majority of the modules emissions coming from electricity, JA's total emissions decrease if China increases their nation wide renewable energy capacity.

JA's module is similar to the general Chinese module described in the IEA's LCI. The only difference is in the electricity mix for the cell and module process. It is likely that JA's module has more differences in their production, but because of trade secrets and lack of public information, gathering information to create a more accurate LCI to reflect these differences were not possible.

10.5 Risen Energy

Risen Energy produces a panel with a proclaimed carbon footprint of less than 400 kg CO_2-eq/kWp. It is unclear as to exactly how common this panel is and it may be that it does not represent the average panel produced by Risen. This LCA does not represent the production of this specific Risen module. However, it is important to note that Risen has panels with significantly lower CFP than the results of this thesis shows. This may be an indication that the results of this LCA is based on outdated inputs and in reality the CFP from a Risen module may be lower than calculated.

A significant uncertainty with Risen's results is in the steel frame inputs. Risen has stated that they utilise a steel frame, and that steel has 4.5 times less emissions. However, it does not say how much of a reduction is achieved by switching from aluminium to steel. Since steel has a higher density than aluminium, it could be argued that it would require a higher weight based input to fill the same frame as the lighter aluminium. Another argument could be made that steel is a more sturdy material, and therefore the frame could be made thinner. It is also uncertain as to what type of steel alloy is used. It could contain everything from 0-50% of other materials. Because of all these uncertainties, the weight based input remains the same for steel as for aluminium, and a standard Simapro steel alloy has been chosen, as shown in Table 8.4.

10.5.1 Future supply chain

Risen Energy's production may be subject to significant change over the coming years. Risen has a large projected expansion planned. Their production of cells and modules will increase from 22.1 GW to 44 and 39 GW respectively before 2030. Risen is also working towards gaining higher independence in their supply chain, by expanding their production to include raw material extraction and refining. This may be partly done as to avoid both forced labour accusations and price fluctuations in the polysilicon market.

Risen is also expanding its energy self sufficiency by building renewable energy plants close to their production in Inner Mongolia. It is however uncertain as to how much of their own production they will supply with clean electricity. A change in the electricity mix will drastically reduce the production related emissions of modules from this plant. If Risen manages to make a totally vertical production chain with renewable energy as the main energy source, these modules will become significantly more sustainable both from an environmental and from a social impact point of view.

10.6 Hanwha Qcells

Qcells total emissions was 418 kg CO_2-eq/kWp, where approximately 155 kg of this was due to electricity based emissions. Table 9.2 clearly shows the effect using hydro power has on the total emissions. When utilising hydro power, the most electricity intensive processes, polysilicon and ingot manufacturing, has noticeably low emission levels. This is a clear case of how utilising renewable energy sources in manufacturing significantly improves the environmental sustainability of a module.

Due to the significance of OCI using hydro power in their manufacturing, the assumption that OCI is Qcells' sole supplier has a large impact on the results. No sources were found that implicated that Qcells has another supplier. If this had been the case, and that supplier was not utilising a totally renewable energy source, the CO_2-eq emissions could significantly increase, depending on the electricity mix used. As no other long term suppliers has been discovered, it is safest to assume OCI as sole supplier.

Another assumption concerning electricity sources was centred around the electricity mix in Georgia in the US. Since no Simapro input existed for the state of Georgia, an electricity mix was simulated based on data from the organisation Electricity Maps. One flaw regarding this assumption, is that it is based on another assumption being that Electricity Maps calculated emissions using the same method as Simapro. If this is not the case, the electricity mixes are not necessarily comparable. However, as the Georgia electricity only represents 8.55 kg of the total emissions, as presented in Figure 9.7, a difference in calculation method would likely have little impact on the results.

10.6.1 Supply chain

The two first steps of Qcells' supply chain is largely assumed. There is little evidence connecting OCI with Hoshine, therefore this is the most uncertain part of the supply chain. However, if this assumption was proved to be untrue, it would likely have positive results for Qcells' total sustainability. Hoshine and Shanshan Stone Industrial Park has manufacturing plants in Xinjiang, which is both the location of China's forced labour programs and the largest coal deposits in China. If it turned out OCI was supplied by other companies located outside of Xinjiang they would likely use less coal in the electricity mix.

Concerning the levels of forced labour exposure in Qcells supply chain, there are no strong links between Qcells' production and forced labour. From SoG-Si refining to module manufacturing, there is only one manufacturing plant located in China. This plant is in Jiangsu, a province with no connection to forced labour programs. From raw material extraction to MG-Si production, both Hoshine and Shanshan Stone Industrial Park are accused of utilising forced labour. With the weak evidence connecting Hoshine and OCI, the chain of production of a Qcells module has a low probability of utilising forced labour. If the evidence connecting Hoshine and OCI turns out to be incorrect and OCI uses a non-Xinjiang based MG-Si and quartz supplier, there would be no direct or indirect ties to forced labour in the supply chain.

10.6.2 Future supply chain

Qcells is the most sustainable company assessed in this thesis. However, Qcells is the least ambitious of the three regarding expanding their production capacity. It might be argued that Qcells' relatively small size enables them to easier make sustainable choices. With JA Solar's module production capacity of 37 GW and projected plans for 32 GW additionally, establishing large enough deals with other suppliers than for example Hoshine and Daqo, would be a major challenge. Qcells module production capacity of 12.4 GW with 6.7 GW projected would be easier to supply by other, smaller and more sustainable companies.

Qcells plans to establish a fully US based supply chain is a step towards reducing the worlds dependence on China in the PV market, but it does not necessarily mean improved environmental sustainability. As presented in Section 8.4, the electricity emission levels vary greatly across the US. The environmental sustainability of the new US produced modules would depend on the production either being based in states with relatively low-emission grid mixes or having direct access to renewable energy plants.

10.7 Future market

The PV industry is one of the fastest growing industries in the world. The market has a massive yearly growth and the industry is rapidly inventing new and better technology. This rapid expansion in production and technology, combined with a lack of up to date production data makes it difficult to analyse the current market. This analysis will probably reflect an older market than the current one. It is therefore important to analyse projected changes and trends in the market to gain a better understanding of how the industry and the market will look in the next couple of years.

As of 2023, China dominates the whole supply chain for manufacturing PV modules. Even though both the EU and the US is working to establish their own supply chains, the production planned by the Chinese companies outweigh that of EU an the US. However, companies such as

JA, Risen and others are increasingly becoming more socially and environmentally sustainable, to better meet the stricter demands from importing countries. Because of this, many PV manufacturing companies are looking to establish their new production at places, either with an already clean energy mix, or with space for building renewable energy.

The development in the European and American market will also play a decisive factor in the sustainability of the sector. If the newly planned increase in western production capacity manages to become economically sustainable, it may change the internal competition in the market. Even though the Chinese companies are likely to dominate the market for a long time, the presence of new companies with stricter environmental standards, might push the market in a more sustainable direction.

Another change that might affect the global supply chain is if more countries follows France and South Korea in implementing strict CFP certifications of solar installations, as mentioned in Section 5.2.4. These certifications give advantages to the more environmentally sustainable modules in the bidding process of larger solar installations. This gives production companies incentive to optimise their CFP to not risk losing the bidding process to companies with a higher CFP, because they have lower costs. If more countries implemented similar restrictions, it would not only set a precedence for including CFP in future regulations of renewable energy, but also put pressure on even more companies to optimise their CFP.

A more competitive market might lead to a more rapid development of new technology and recycling. Innovation such as FBR production and kerf recycling are examples of technology that is not yet utilised at a large scale. A more widespread utilisation of these kinds of innovations could push the industry in a more sustainable direction. It could also become a niche in which smaller European and American companies gain a competitive advantage over the already established companies.

10.8 Further studies

This thesis is a project limited by time, resources and information available. Therefore there are some areas of the subject which were not thoroughly explored. These subjects was not possible to research sufficiently in this report, but is still strongly relevant to the general subject matter. Therefore, in the case of possible further studies, the following subjects should be explored.

The assessment done in this thesis has cradle to gate set as its system boundary, with the majority of the focus being on the last stages of solar manufacturing, producing cells and modules. For this thesis, the data required to establish all manufacturing locations of the production stages preceding cell production, was not available. This would however have led to a more specific LCA, and with additional time available, more in depth research of manufacturing locations should be considered for further studies.

If all upstream supplier locations were found, it would be possible to expand the scope of the LCA to include transport. This report has focused on a company average of a specific PV module, through the use of a calculated average electricity mix. However, if choosing an individual module originating from one manufacturing plant, it would be possible to map a location specific supply chain for the individual module, and include specific transport routes.

An additional step to improve the thesis is to expand the scope to a cradle to grave LCA, to look at the modules' end of life. An interesting aspect to analyse would be the recycling and reuse of PV modules. There is an increase in research on how to further the recyclability of modules. Using these recycled materials again in the PV module production would reduce the total emissions of the module. As for the reuse, even though the economical lifespan of a PV module is around 25 to 30 years, they are often still operational after that period. These panels might be reused in other markets. Therefore, a closer analysis of the end of life could provide an interesting insight into the life cycle of a PV module.

Gaining more detailed knowledge on the inputs for each individual module would enable more specific results of the LCA. This information could include specific process differences in the production of the modules and specific material use differing from the IEA's LCI. As the main difference between the modules in this assessment is the electricity mix used in production, the difference between the modules is mainly seen in the GWP. More detailed inputs might enhance the differences in the modules' impacts regarding impact categories such as human health, land use and particulate matter emissions. This would result in a more detailed comparison of the companies.

An economical aspect has not been considered in this thesis. The prices publicly available per module is not comparable with the price per module when ordering in large quantities, such as Aneo would for a solar installation. As such, including a price comparison in the thesis would not accurately reflect the real evaluation done by Aneo when choosing modules. However, by omitting the prices of the modules there is a possibility that the panels compared are similar in efficiency and size, but not in price. For example, the Qcells module had the least emissions and connection to forced labour. However, if the Qcells module is significantly more expensive, the price would have to be weighed against the sustainability when deciding between the modules. For further studies, an economical aspect included in the comparison would enable Aneo to make a decisions based on more criteria than that of environmental and social impact.

11 Conclusion

The climate crisis has caused an urgent and growing demand for renewable energy production. With the solar power portion of the global energy production rapidly increasing, the focus on sustainability within the PV production is also growing. As this thesis analyses the global PV market and supply chains, both the environmental sustainability in the form of CO_2 emissions, and the social sustainability in the form of exposure to forced labour practices has been examined.

Comparing the three companies, JA Solar has both the largest production capacity and the largest emission level with 667 kg CO_2-eq/kWp. The production is mainly based in China, but with no manufacturing in Xinjiang. JA is indirectly connected to the use of forced labour through their upstream suppliers, Xinte, GCL-Poly, Hoshine, Sokesi and Tianye. They have not announced any plans to change their supply chains in the near future.

The Risen Energy module has a lower emission level than JA Solar, with 618 kg CO_2-eq/kWp, due in large part to different material use in the frame. With the majority of the supply chain based in China, Risen Energy has the same connections to forced labour as JA Solar through the same upstream suppliers. However, the company intends to gain greater autonomy of parts of their supply chain, by independently manufacturing parts of all stages of production as well as generating renewable energy at their projected Inner Mongolia factory. It is however uncertain how much of their supply chain they will produce independently and how much will remain the same.

Hanwha Qcells has the lowest production capacity of the three companies, in addition to the lowest emissions of 418 kg CO_2-eq/kWp. Qcells has the majority of its supply chain based outside of China, and the company is only exposed to forced labour through a weak connection to Hoshine. In the future, Qcells plans to expand production in the US, where they will also commence ingot and wafer manufacturing.

China has, and will likely continue to have, a significant market share of the PV industry. However, both the EU and the US has announced plans or implemented policies to strengthen the domestic PV industry. As these policies are still in their infancy, it is unsure how these markets will evolve in the coming years. Parallel to this, CFP regulations and forced labour prevention policies increases the pressure on manufacturers to improve their sustainability.

Based on the findings on environmental and social sustainability in this thesis, the Hanwha Qcells module is the better option. However, through Risen's projected production in Inner Mongolia, they have the potential to create low-carbon modules free of forced labour. Similar for all three companies, is that their already established production will still have ties to forced labour for the foreseeable future.

As this thesis focuses on just these three module manufacturers, to make an informed decision on other modules, the existing regulations and restrictions can be used as tools assess the environmental and social sustainability of modules. A module with a CFP certifications from France or South Korea, that is not on the UFLPA entity list of companies exposed to forced labour would be a safe choice for a solar power company wanting to ensure using a sustainable module.

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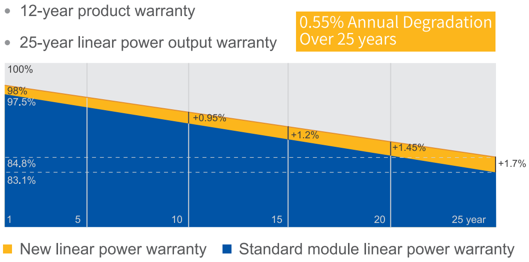
- Higher output power
- Lower LCOE
- Less shading and lower resistive loss
- Better mechanical loading tolerance

Superior Warranty

- 12-year product warranty
- 25-year linear power output warranty



Comprehensive Certificates

- IEC 61215, IEC 61730
- ISO 9001: 2015 Quality management systems
- ISO 14001: 2015 Environmental management systems
- ISO 45001: 2018 Occupational health and safety management systems

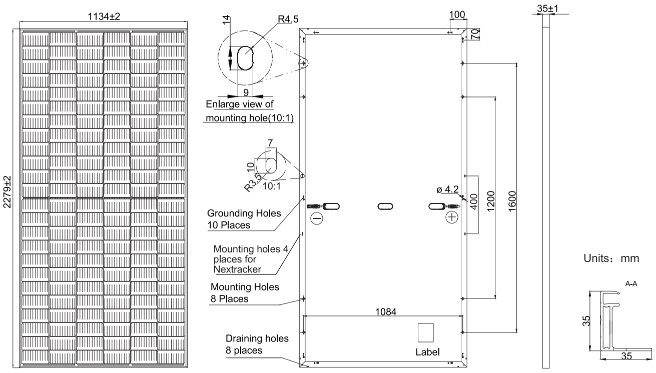
JA SOLAR

www.jasolar.com
Specifications subject to technical changes and tests.
JA Solar reserves the right of final interpretation.
Shanghai JA Solar Technology Co., Ltd.

JA SOLAR

JAM72S30 525-550/MR/1500V Series

MECHANICAL DIAGRAMS



Remark: customized frame color and cable length available upon request

SPECIFICATIONS

Cell	Mono
Weight	28.6kg±3%
Dimensions	2279±2mm×1134±2mm×35±1mm
Cable Cross Section Size	4mm²（IEC），12 AWG(UL)
No. of cells	144(6×24）
Junction Box	IP68, 3 diodes
Connector	Genuine MC4-EVO2 QC 4.10-35/45
Cable Length (Including Connector)	Portrait: 300mm(+)/400mm(-); Landscape: 1300mm(+)/1300mm(-)
Country of Manufacturer	China/Vietnam

ELECTRICAL PARAMETERS AT STC

TYPE	JAM72S30 -525/MR/1500V	JAM72S30 -530/MR/1500V	JAM72S30 -535/MR/1500V	JAM72S30 -540/MR/1500V	JAM72S30 -545/MR/1500V	JAM72S30 -550/MR/1500V
Rated Maximum Power(Pmax) [W]	525	530	535	540	545	550
Open Circuit Voltage(Voc) [V]	49.15	49.30	49.45	49.60	49.75	49.90
Maximum Power Voltage(Vmp) [V]	41.15	41.31	41.47	41.64	41.80	41.96
Short Circuit Current(Isc) [A]	13.65	13.72	13.79	13.86	13.93	14.00
Maximum Power Current(Imp) [A]	12.76	12.83	12.90	12.97	13.04	13.11
Module Efficiency [%]	20.3	20.5	20.7	20.9	21.1	21.3
Power Tolerance	0~+5W					
Temperature Coefficient of Isc(α_Isc)	+0.045%℃					
Temperature Coefficient of Voc(β_Voc)	-0.275%/℃					
Temperature Coefficient of Pmax(γ_Pmp)	-0.350%/℃					
STC	Irradiance 1000W/m², cell temperature 25℃, AM1.5G					

Remark: Electrical data in this catalog do not refer to a single module and they are not part of the offer.They only serve for comparison among different module types. Measurement tolerance at STC: Pmax ±3 %, Voc ±3% and Isc ±4%.

ELECTRICAL PARAMETERS AT NOCT

TYPE	JAM72S30-525 /MR/1500V	JAM72S30-530 /MR/1500V	JAM72S30-535 /MR/1500V	JAM72S30-540 /MR/1500V	JAM72S30-545 /MR/1500V	JAM72S30-550 /MR/1500V
Rated Max Power(Pmax) [W]	397	401	405	408	412	416
Open Circuit Voltage(Voc) [V]	46.05	46.18	46.31	46.43	46.55	46.68
Max Power Voltage(Vmp) [V]	38.36	38.57	38.78	38.99	39.20	39.43
Short Circuit Current(Isc) [A]	10.97	11.01	11.05	11.09	11.13	11.17
Max Power Current(Imp) [A]	10.35	10.39	10.43	10.47	10.51	10.55
NOCT	Irradiance 800W/m², ambient temperature 20℃,wind speed 1m/s, AM1.5G					

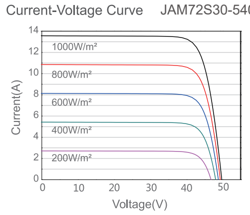
OPERATING CONDITIONS

Maximum System Voltage	1500V DC (IEC)
Operating Temperature	-40℃~+85℃
Maximum Series Fuse Rating	25A
Maximum Static Load,Front* Maximum Static Load,Back*	3600Pa, 1.5 1600Pa, 1.5
NOCT	45±2℃
Safety Class	Class Ⅱ
Fire Performance	UL Type 1

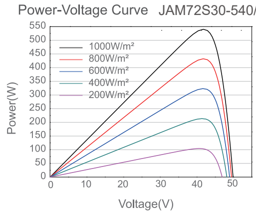
*For NexTracker installations, Maximum Static Load, Front is 2000Pa while Maximum Static Load, Back is2000Pa .

CHARACTERISTICS

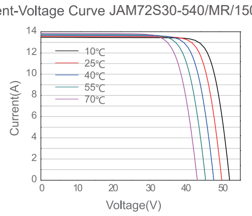
Current-Voltage Curve JAM72S30-540/MR/1500V



Power-Voltage Curve JAM72S30-540/MR/1500V



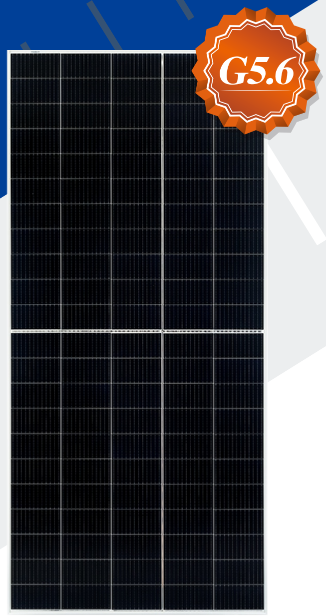
Current-Voltage Curve JAM72S30-540/MR/1500V



Premium Cells, Premium Modules Version No. : Global_EN_20210607A

TITAN

HIGH PERFORMANCE MONOCRYSTALLINE PERC MODULE



RSM110-8-535M-560M

110 CELL Mono PERC Module	**535-560Wp** Power Output Range
1500VDC Maximum System Voltage	**21.4%** Maximum Efficiency

KEY SALIENT FEATURES

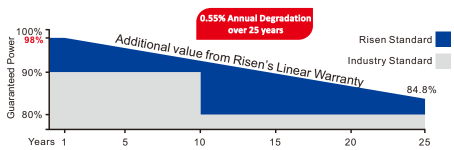
- Global, Tier 1 bankable brand, with independently certified state-of-the-art automated manufacturing
- Industry leading lowest thermal co-efficient of power
- Industry leading 12 years product warranty
- Excellent low irradiance performance
- Excellent PID resistance
- Positive power tolerance of 0~+3%
- Dual stage 100% EL Inspection warranting defect-free product
- Module Imp binning radically reduces string mismatch losses
- Excellent wind load 2400Pa & snow load 5400Pa under certain installation method
- Comprehensive product and system certification
  - IEC61215:2016; IEC61730-1/-2:2016;
  - ISO 9001:2015 Quality Management System
  - ISO 14001:2015 Environmental Management System
  - ISO 45001:2018 Occupational Health and Safety Management System

ISO9001
ISO14001
ISO45001
IEC62941

★ As there are different certification requirements in different markets, please contact your local Risen Energy sales representative for the specific certificates applicable to the products in the region in which the products are to be used.

LINEAR PERFORMANCE WARRANTY

12 year Product Warranty / 25 year Linear Power Warranty



★ Please check the valid version of Limited Product Warranty which is officially released by Risen Energy Co., Ltd

RISEN ENERGY CO., LTD.

Risen Energy is a leading, global tier 1 manufacturer of high-performance solar photovoltaic products and provider of total business solutions for residential, commercial and utility-scale power generation. The company, founded in 1986, and publicly listed in 2010, compels value generation for its chosen global customers. Techno-commercial innovation, underpinned by consummate quality and support, encircle Risen Energy's total Solar PV business solutions which are among the most powerful and cost-effective in the industry. With local market presence and strong financial bankability status, we are committed, and able, to building strategic, mutually beneficial collaborations with our partners, as together we capitalise on the rising value of green energy.

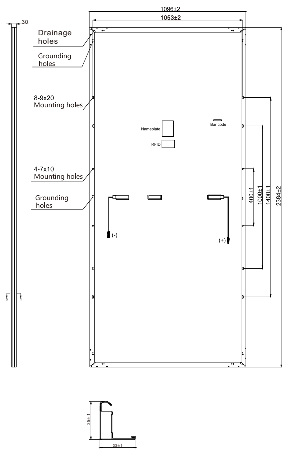
Tashan Industry Zone, Meilin, Ninghai 315609,Ningbo | PRC
Tel: +86-574-59953239 Fax: +86-574-59953599
E-mail: marketing@risenenergy.com Website: www.risenenergy.com

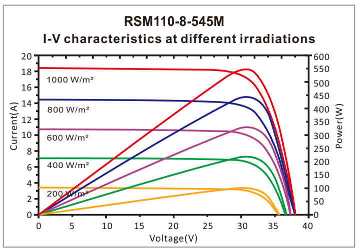
risen

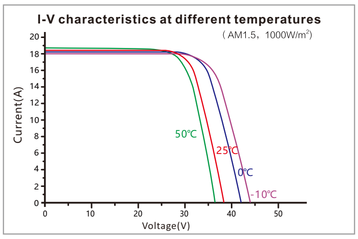
THE POWER OF RISING VALUE

TITAN

Dimensions of PV Module Unit: mm







Our Partners:

REM110-M-12BB-EN-H1-1-2023

ELECTRICAL DATA (STC)

Model Number	RSM110-8-535M	RSM110-8-540M	RSM110-8-545M	RSM110-8-550M	RSM110-8-555M	RSM110-8-560M
Rated Power in Watts-Pmax(Wp)	**535**	**540**	**545**	**550**	**555**	**560**
Open Circuit Voltage-Voc(V)	37.58	37.78	38.02	38.24	38.46	38.68
Short Circuit Current-Isc(A)	18.13	18.18	18.23	18.28	18.33	18.38
Maximum Power Voltage-Vmpp(V)	31.26	31.46	31.66	31.86	32.06	32.26
Maximum Power Current-Impp(A)	17.12	17.17	17.22	17.27	17.32	17.37
Module Efficiency (%) ★	20.5	20.7	20.9	21.0	21.2	21.4

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5 according to EN 60904-3.
★ Module Efficiency (%): Round-off to the nearest number

ELECTRICAL DATA (NMOT)

Model Number	RSM110-8-535M	RSM110-8-540M	RSM110-8-545M	RSM110-8-550M	RSM110-8-555M	RSM110-8-560M
Maximum Power-Pmax (Wp)	405.3	409.0	412.8	416.7	420.5	424.3
Open Circuit Voltage-Voc (V)	34.95	35.14	35.36	35.56	35.77	35.97
Short Circuit Current-Isc (A)	14.87	14.91	14.95	14.99	15.03	15.07
Maximum Power Voltage-Vmpp (V)	29.01	29.19	29.38	29.57	29.75	29.94
Maximum Power Current-Impp (A)	13.97	14.01	14.05	14.09	14.13	14.17

NMOT: Irradiance at 800 W/m², Ambient Temperature 20°C, Wind Speed 1 m/s.

MECHANICAL DATA

Solar cells	Monocrystalline
Cell configuration	110 cells (5×11+5×11)
Module dimensions	2384×1096×30mm
Weight	30.5kg
Superstrate	High Transmission, Low Iron, AR Coated Heat Strengthened Glass
Substrate	White Back-sheet
Frame	High strength alloy steel
J-Box	Potted, IP68, 1500VDC, 3 Schottky bypass diodes
Cables	4.0mm², Positive(+)350mm, Negative(-)230mm (Connector Included)
Connector	Risen Twinsel PV-SY02, IP68

TEMPERATURE & MAXIMUM RATINGS

Nominal Module Operating Temperature (NMOT)	44°C±2°C
Temperature Coefficient of Voc	-0.25%/°C
Temperature Coefficient of Isc	0.04%/°C
Temperature Coefficient of Pmax	-0.34%/°C
Operational Temperature	-40°C~+85°C
Maximum System Voltage	1500VDC
Max Series Fuse Rating	30A
Limiting Reverse Current	30A

PACKAGING CONFIGURATION

	40ft(HQ)
Number of modules per container	700
Number of modules per pallet	35
Number of pallets per container	20
Packaging box dimensions (LxWxH) in mm	2395×1075×1235
Box gross weight[kg]	1090

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

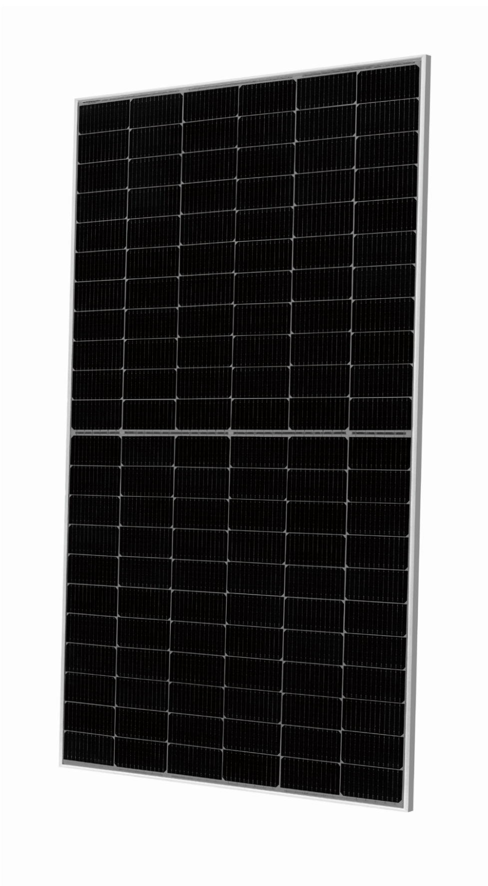
THE POWER OF RISING VALUE

Q.PEAK DUO ML-G11S+ SERIES

Qcells

490 - 510 Wp | 132 Cells
21.5 % Maximum Module Efficiency

MODEL Q.PEAK DUO ML-G11S.2+



Breaking the 21 % efficiency barrier

Q.ANTUM DUO Technology with optimized module layout boosts module power.

A reliable investment

Inclusive 25-year product warranty and 25-year linear performance warranty[1].

Enduring high performance

Long-term yield security with Anti LeTID Technology, Anti PID Technology[2], and Hot-Spot Protect.

Extreme weather rating

High-tech aluminium alloy frame, certified for high snow (5400 Pa) and wind loads (3000 Pa).

Innovative all-weather technology

Optimal yields, whatever the weather with excellent low-light and temperature behaviour.

The most thorough testing programme in the industry

Qcells is the first solar module manufacturer to pass the most comprehensive quality programme in the industry: The new "Quality Controlled PV" of the independent certification institute TÜV Rheinland.

[1] See data sheet on rear for further information.
[2] APT test conditions according to IEC / TS 62804-1:2015, method A (−1500 V, 96 h)

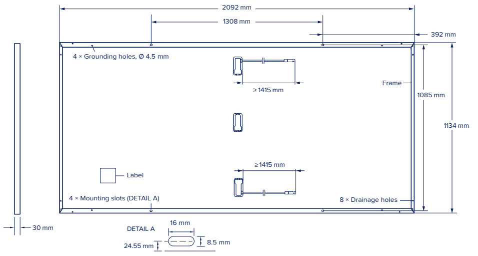
The ideal solution for:

Rooftop arrays on commercial/industrial buildings

Q.PEAK DUO ML-G11S+ SERIES

Mechanical Specification

Format	2092 mm × 1134 mm × 30 mm (including frame)
Weight	25.7 kg
Front Cover	3.2 mm thermally pre-stressed glass with anti-reflection technology
Back Cover	Composite film
Frame	Anodized aluminium
Cell	6 × 22 monocrystalline Q.ANTUM solar half cells
Junction box	53-101 mm × 32-60 mm × 15-18 mm Protection class IP67, with bypass diodes
Cable	4 mm² Solar cable; (+) ≥1415 mm, (−) ≥1415 mm
Connector	Stäubli MC4-Evo2, Hanwha Q CELLS HQC4; IP68

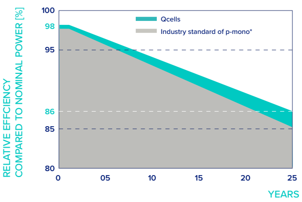


Electrical Characteristics

POWER CLASS			490	495	500	505	510
MINIMUM PERFORMANCE AT STANDARD TEST CONDITIONS, STC[1] (POWER TOLERANCE +5 W / −0 W)							
Minimum: Power at MPP[1]	P_{MPP}	[W]	490	495	500	505	510
Minimum: Short Circuit Current[1]	I_{SC}	[A]	13.88	13.91	13.94	13.97	14.00
Minimum: Open Circuit Voltage[1]	V_{OC}	[V]	45.30	45.32	45.35	45.38	45.41
Minimum: Current at MPP	I_{MPP}	[A]	13.16	13.22	13.28	13.34	13.39
Minimum: Voltage at MPP	V_{MPP}	[V]	37.23	37.44	37.66	37.87	38.08
Minimum: Efficiency[1]	η	[%]	≥20.7	≥20.9	≥21.1	≥21.3	≥21.5
MINIMUM PERFORMANCE AT NORMAL OPERATING CONDITIONS, NMOT[2]							
Minimum: Power at MPP	P_{MPP}	[W]	367.6	371.4	375.1	378.9	382.6
Minimum: Short Circuit Current	I_{SC}	[A]	11.18	11.21	11.23	11.26	11.28
Minimum: Open Circuit Voltage	V_{OC}	[V]	42.72	42.74	42.77	42.79	42.82
Minimum: Current at MPP	I_{MPP}	[A]	10.35	10.40	10.45	10.50	10.55
Minimum: Voltage at MPP	V_{MPP}	[V]	35.52	35.71	35.89	36.07	36.25

[1]Measurement tolerances P_{MPP} ±3%; I_{SC}; V_{OC} ±5% at STC: 1000 W/m², 25±2 °C, AM 1.5 according to IEC 60904-3 • [2]800 W/m², NMOT, spectrum AM 1.5

Qcells PERFORMANCE WARRANTY

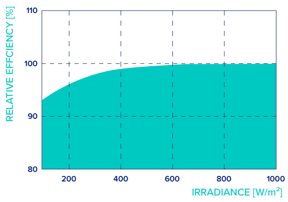


At least 98 % of nominal power during first year. Thereafter max. 0.5 % degradation per year. At least 93.5 % of nominal power up to 10 years. At least 86 % of nominal power up to 25 years.

All data within measurement tolerances. Full warranties in accordance with the warranty terms of the Qcells sales organisation of your respective country.

*Standard terms of guarantee for the 5 PV companies with the highest production capacity in 2021 (February 2021)

PERFORMANCE AT LOW IRRADIANCE



Typical module performance under low irradiance conditions in comparison to STC conditions (25 °C, 1000 W/m²).

TEMPERATURE COEFFICIENTS

Temperature Coefficient of I_{SC}	α	[% / K]	+0.04	Temperature Coefficient of V_{OC}	β	[% / K]	−0.27
Temperature Coefficient of P_{MPP}	γ	[% / K]	−0.34	Nominal Module Operating Temperature	NMOT	[°C]	43±3

Properties for System Design

Maximum System Voltage	V_{SYS}	[V]	1500	PV module classification	Class II
Maximum Reverse Current	I_R	[A]	25	Fire Rating based on ANSI / UL 61730	C / TYPE 1
Max. Design Load, Push / Pull		[Pa]	3600 / 2000	Permitted Module Temperature on Continuous Duty	−40 °C - +85 °C
Max. Test Load, Push / Pull		[Pa]	5400 / 3000		

Qualifications and Certificates

Quality Controlled PV - TÜV Rheinland;
IEC 61215:2016;
IEC 61730:2016.
This data sheet complies with DIN EN 50380.

TÜVRheinland CERTIFIED www.tuv.com ID 1111220277

UK CA CE

Qcells pursues minimizing paper output in consideration of the global environment.

Note: Installation instructions must be followed. Contact our technical service for further information on approved installation of this product.

Hanwha Q CELLS GmbH Sonnenallee 17-21, 06766 Bitterfeld-Wolfen, Germany | TEL +49 (0)3494 66 99-23444 | FAX +49 (0)3494 66 99-23000 | EMAIL sales@q-cells.com | WEB www.qcells.com

qcells

D APPENDIX: D

3.2.4 Basic Silicon Products

Basic Silicon Products

The first stage in the photovoltaic supply chain is the production of metallurgical grade silicon (MG-silicon). Table 6 shows the unit process data of the MG-Silicon production in Europe (NO), China (CN), North America (US) and Asia & Pacific (APAC). European MG-silicon factories are located in Norway, which implies use of the Norwegian electricity mix. The South Korean electricity mix is selected for the APAC region, because South Korea produces the highest share of MG-Silicon in the APAC region. The US electricity mix is used to model electricity consumption in the North American production.

Data about material and energy consumption as well as about emissions correspond to the life cycle inventory data of MG-silicon published by Frischknecht et al. [19].

Table 6: Unit process LCI data of MG-Silicon production in Europe (NO), China (CN), North America (US) and Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	MG-silicon, at plant	MG-silicon, at plant	MG-silicon, at plant	MG-silicon, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				NO	CN	US	APAC			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	MG-silicon, at plant	NO	0	kg	1	0	0	0			
	MG-silicon, at plant	CN	0	kg	0	1	0	0			
	MG-silicon, at plant	US	0	kg	0	0	1	0			
	MG-silicon, at plant	APAC	0	kg	0	0	0	1			
technosphere	electricity, medium voltage, at grid	NO	0	kWh	1.10E+1	0	0	0	1	1.22	(2,2,4,1,1,3); Literature, lower range to account for heat recovery
	electricity, medium voltage, at grid	CN	0	kWh	0	1.10E+1	0	0	1	1.22	(2,2,4,1,1,3); Literature, lower range to account for heat recovery
	electricity, medium voltage, at grid	US	0	kWh	0	0	1.10E+1	0	1	1.22	(2,2,4,1,1,3); Literature, lower range to account for heat recovery
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	1.10E+1	1	1.22	(2,2,4,1,1,3); Literature, lower range to account for heat recovery
	wood chips, production mix, wet, measured as dry mass, at forest road & at sawmill	RER	0	kg	3.25E-3	3.25E-3	3.25E-3	3.25E-3	1	1.22	(2,2,4,1,1,3); Literature, 1.35 kg
	hard coal coke, at plant	RER	0	MJ	2.31E+1	2.31E+1	2.31E+1	2.31E+1	1	1.22	(2,2,4,1,1,3); Literature, coal
	graphite, at plant	RER	0	kg	1.00E-1	1.00E-1	1.00E-1	1.00E-1	1	1.22	(2,2,4,1,1,3); Literature, graphite electrodes
	charcoal, at plant	GLO	0	kg	1.70E-1	1.70E-1	1.70E-1	1.70E-1	1	1.22	(2,2,4,1,1,3); Literature
	petroleum coke, at refinery	RER	0	kg	5.00E-1	5.00E-1	5.00E-1	5.00E-1	1	1.22	(2,2,4,1,1,3); Literature
	silica sand, at plant	DE	0	kg	2.70E+0	2.70E+0	2.70E+0	2.70E+0	1	1.22	(2,2,4,1,1,3); Literature
	oxygen, liquid, at plant	RER	0	kg	2.00E-2	2.00E-2	2.00E-2	2.00E-2	1	1.60	(3,4,5,3,1,5); Literature
	disposal, slag from MG silicon production, 0% water, to inert material landfill	CH	0	kg	2.50E-2	2.50E-2	2.50E-2	2.50E-2	1	1.22	(2,2,4,1,1,3); Literature
	silicone plant	RER	1	unit	1.00E-11	1.00E-11	1.00E-11	1.00E-11	1	3.09	(1,2,4,1,3,3); Estimation
	transport, transoceanic freight ship	OCE	0	tkm	2.55E+0	2.55E+0	2.55E+0	2.55E+0	1	2.09	(4,5,na,na,na,na); Charcoal from Asia 15000km
	transport, freight, lorry, fleet average	RER	0	tkm	1.56E-1	1.56E-1	1.56E-1	1.56E-1	1	2.09	(4,5,na,na,na,na); Standard distance 50km, 20km for sand
	transport, freight, rail	RER	0	tkm	6.90E-2	6.90E-2	6.90E-2	6.90E-2	1	2.09	(4,5,na,na,na,na); Standard distance 100km
emission air, low population density	Heat, waste	-	-	MJ	7.13E+1	7.13E+1	7.13E+1	7.13E+1	1	1.22	(2,2,4,1,1,3); Calculation based on fuel and electricity use minus 25 MJ/kg
	Arsenic	-	-	kg	9.42E-9	9.42E-9	9.42E-9	9.42E-9	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Aluminium	-	-	kg	1.55E-6	1.55E-6	1.55E-6	1.55E-6	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Antimony	-	-	kg	7.85E-9	7.85E-9	7.85E-9	7.85E-9	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Boron	-	-	kg	2.79E-7	2.79E-7	2.79E-7	2.79E-7	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Cadmium	-	-	kg	3.14E-10	3.14E-10	3.14E-10	3.14E-10	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Calcium	-	-	kg	7.75E-7	7.75E-7	7.75E-7	7.75E-7	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Carbon monoxide, biogenic	-	-	kg	6.20E-4	6.20E-4	6.20E-4	6.20E-4	1	5.34	(3,4,5,3,1,5); Literature
	Carbon monoxide, fossil	-	-	kg	1.38E-3	1.38E-3	1.38E-3	1.38E-3	1	5.34	(3,4,5,3,1,5); Literature
	Carbon dioxide, biogenic	-	-	kg	1.61E+0	1.61E+0	1.61E+0	1.61E+0	1	1.22	(2,2,4,1,1,3); Calculation, biogenic fuels
	Carbon dioxide, fossil	-	-	kg	3.58E+0	3.58E+0	3.58E+0	3.58E+0	1	1.22	(2,2,4,1,1,3); Calculation, fossil fuels
	Chromium	-	-	kg	7.85E-9	7.85E-9	7.85E-9	7.85E-9	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Chlorine	-	-	kg	7.85E-8	7.85E-8	7.85E-8	7.85E-8	1	1.85	(3,4,5,3,1,5); Literature
	Cyanide	-	-	kg	6.87E-6	6.87E-6	6.87E-6	6.87E-6	1	1.85	(3,4,5,3,1,5); Estimation
	Fluorine	-	-	kg	3.88E-8	3.88E-8	3.88E-8	3.88E-8	1	1.85	(3,4,5,3,1,5); Literature, in dust
	Hydrogen sulfide	-	-	kg	5.00E-4	5.00E-4	5.00E-4	5.00E-4	1	1.85	(3,4,5,3,1,5); Estimation
	Hydrogen fluoride	-	-	kg	5.00E-4	5.00E-4	5.00E-4	5.00E-4	1	1.85	(3,4,5,3,1,5); Estimation
	Iron	-	-	kg	3.88E-6	3.88E-6	3.88E-6	3.88E-6	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Lead	-	-	kg	3.44E-7	3.44E-7	3.44E-7	3.44E-7	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Mercury	-	-	kg	7.85E-9	7.85E-9	7.85E-9	7.85E-9	1	5.34	(3,4,5,3,1,5); Literature, in dust
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.60E-5	9.60E-5	9.60E-5	9.60E-5	1	1.85	(3,4,5,3,1,5); Literature
	Nitrogen oxides	-	-	kg	9.74E-3	9.74E-3	9.74E-3	9.74E-3	1	1.58	(3,2,4,1,1,3); Calculation based on environmental report
	Particulates, > 10 um	-	-	kg	7.75E-3	7.75E-3	7.75E-3	7.75E-3	1	1.58	(3,2,4,1,1,3); Calculation based on environmental report
	Potassium	-	-	kg	6.20E-5	6.20E-5	6.20E-5	6.20E-5	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Silicon	-	-	kg	7.51E-3	7.51E-3	7.51E-3	7.51E-3	1	5.34	(3,4,5,3,1,5); Literature, SiO2 in dust
	Sodium	-	-	kg	7.75E-7	7.75E-7	7.75E-7	7.75E-7	1	5.34	(3,4,5,3,1,5); Literature, in dust
	Sulfur dioxide	-	-	kg	1.22E-2	1.22E-2	1.22E-2	1.22E-2	1	1.24	(3,2,4,1,1,3); Calculation based on environmental report
	Tin	-	-	kg	7.85E-9	7.85E-9	7.85E-9	7.85E-9	1	5.34	(3,4,5,3,1,5); Literature, in dust

Solar grade silicon

D APPENDIX: D

Table 7 shows the unit process data of solar grade silicon production in Europe (RER), China (CN), North America (US) and Asia & Pacific (APAC). The South Korean electricity mix is selected for the APAC region, because South Korea produces the highest share of solar grade silicon in the APAC region. Electricity from hydro power and from the US grid is chosen to model electricity consumption in the North American production, since one of the most important North American producers mainly relies on hydroelectric power. The thermal energy demand is 8 kWh and the electricity demand is 49 kWh per kg [2].

All other data about material and energy consumption as well as about emissions correspond to the life cycle inventory data of solar grade silicon published in Frischknecht et al. [19].

Table 7: Unit process LCI data of solar grade silicon production in Europe (RER), China (CN), North America (US) and Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	silicon, solar grade, modified Siemens process, at plant	silicon, solar grade, modified Siemens process, at plant	silicon, solar grade, modified Siemens process, at plant	silicon, solar grade, modified Siemens process, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	CN	US	APAC			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	silicon, solar grade, modified Siemens process, at plant	RER	0	kg	1	0	0	0			
	silicon, solar grade, modified Siemens process, at plant	CN	0	kg	0	1	0	0			
	silicon, solar grade, modified Siemens process, at plant	US	0	kg	0	0	1	0			
	silicon, solar grade, modified Siemens process, at plant	APAC	0	kg	0	0	0	1			
technosphere	MG-silicon, at plant	NO	0	kg	1.13E+0	0	0	0	1	1.23	(2,3,4,2,1,3); Literature
	MG-silicon, at plant	CN	0	kg	0	1.13E+0	0	0	1	1.23	(2,3,4,2,1,3); Literature
	MG-silicon, at plant	US	0	kg	0	0	1.13E+0	0	1	1.23	(2,3,4,2,1,3); Literature
	MG-silicon, at plant	APAC	0	kg	0	0	0	1.13E+0	1	1.23	(2,3,4,2,1,3); Literature
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	1.60E+0	1.60E+0	1.60E+0	1.60E+0	1	1.25	(3,3,4,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	hydrogen, liquid, at plant	RER	0	kg	5.01E-2	5.01E-2	5.01E-2	5.01E-2	1	1.25	(3,3,4,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	3.48E-1	3.48E-1	3.48E-1	3.48E-1	1	1.25	(3,3,4,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	transport, freight, lorry, fleet average	RER	0	tkm	2.87E+0	2.87E+0	2.87E+0	2.87E+0	1	2.09	(4,5,na,na,na,na); Transport distance MG-Si: 2000 km; Chemicals: 100 km
	transport, freight, rail	RER	0	tkm	3.65E+0	3.65E+0	3.65E+0	3.65E+0	1	2.09	(4,5,na,na,na,na); Transport distance chemicals: 600 km
	electricity, at cogen 1MWe lean burn, allocation exergy	RER	0	kWh	1.75E+1	0	0	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	3.93E+0	0	1.18E+1	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, medium voltage, at grid	DE	0	kWh	2.23E+1	0	0	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, medium voltage, at grid	NO	0	kWh	5.37E+0	0	0	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, medium voltage, at grid	CN	0	kWh	0	4.90E+1	0	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, medium voltage, at grid	US	0	kWh	0	0	3.72E+1	0	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	4.90E+1	1	1.10	(2,3,1,2,1,3); Total electricity demand: 49 kWh/kg (IEA-PVPS Trends Report 2019)
	heat, at cogen 1MWe lean burn, allocation exergy	RER	0	MJ	2.88E+1	2.88E+1	2.88E+1	2.88E+1	1	1.10	(2,3,1,2,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018; IEA-PVPS Trends Report 2019
	silicone plant	RER	1	unit	1.00E-11	1.00E-11	1.00E-11	1.00E-11	1	3.05	(1,3,4,2,3,3); Estimation
emission air, high population density	Heat, waste	-	-	MJ	1.76E+2	1.76E+2	1.76E+2	1.76E+2	1	1.23	(2,3,4,2,1,3); Calculation
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	1.26E-5	1.26E-5	1.26E-5	1.26E-5	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	BOD5, Biological Oxygen Demand	-	-	kg	2.05E-4	2.05E-4	2.05E-4	2.05E-4	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	COD, Chemical Oxygen Demand	-	-	kg	2.02E-3	2.02E-3	2.02E-3	2.02E-3	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Chloride	-	-	kg	3.60E-2	3.60E-2	3.60E-2	3.60E-2	1	3.14	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Copper	-	-	kg	1.02E-7	1.02E-7	1.02E-7	1.02E-7	1	3.14	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Nitrogen	-	-	kg	2.08E-4	2.08E-4	2.08E-4	2.08E-4	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Phosphate	-	-	kg	2.80E-6	2.80E-6	2.80E-6	2.80E-6	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Sodium, ion	-	-	kg	3.38E-2	3.38E-2	3.38E-2	3.38E-2	1	5.16	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Zinc	-	-	kg	1.96E-6	1.96E-6	1.96E-6	1.96E-6	1	5.16	(4,2,4,1,3,3); Environmental report 2002, average Si product
	Iron	-	-	kg	5.61E-6	5.61E-6	5.61E-6	5.61E-6	1	5.16	(4,2,4,1,3,3); Environmental report 2002, average Si product
	DOC, Dissolved Organic Carbon	-	-	kg	9.10E-4	9.10E-4	9.10E-4	9.10E-4	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product
	TOC, Total Organic Carbon	-	-	kg	9.10E-4	9.10E-4	9.10E-4	9.10E-4	1	1.68	(4,2,4,1,3,3); Environmental report 2002, average Si product

Silicon production mix

D APPENDIX: D

Table 9: Unit process LCI data of the single-crystalline silicon production in Europe (RER), China (CN), North America (US) and Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	CZ single crystalline silicon, photovoltaics, at plant	CZ single crystalline silicon, photovoltaics, at plant	CZ single crystalline silicon, photovoltaics, at plant	CZ single crystalline silicon, photovoltaics, at plant	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CN	US	APAC	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	CZ single crystalline silicon, photovoltaics, at plant	CN	0	kg	1	0	0	0			
	CZ single crystalline silicon, photovoltaics, at plant	US	0	kg	0	1	0	0			
	CZ single crystalline silicon, photovoltaics, at plant	APAC	0	kg	0	0	1	0			
	CZ single crystalline silicon, photovoltaics, at plant	RER	0	kg	0	0	0	1			
technosphere	silicon, production mix, photovoltaics, at plant	CN	0	kg	1.00E+0	0	0	0	1	1.33	(2,4,4,2,1,5); Pot scrap losses (1.5 to 2%, according to Woodhouse (2019)) are accounted for in wafer manufacturing
	silicon, production mix, photovoltaics, at plant	US	0	kg	0	1.00E+0	0	0	1	1.33	(2,4,4,2,1,5); Pot scrap losses (1.5 to 2%, according to Woodhouse (2019)) are accounted for in wafer manufacturing
	silicon, production mix, photovoltaics, at plant	APAC	0	kg	0	0	1.00E+0	0	1	1.33	(2,4,4,2,1,5); Pot scrap losses (1.5 to 2%, according to Woodhouse (2019)) are accounted for in wafer manufacturing
	silicon, production mix, photovoltaics, at plant	GLO	0	kg	0	0	0	1.00E+0	1	1.33	(2,4,4,2,1,5); Pot scrap losses (1.5 to 2%, according to Woodhouse (2019)) are accounted for in wafer manufacturing
materials	argon, liquid, at plant	RER	0	kg	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	hydrogen fluoride, at plant	GLO	0	kg	1.00E-2	1.00E-2	1.00E-2	1.00E-2	1	1.65	(3,4,5,3,3,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	nitric acid, 50% in H2O, at plant	RER	0	kg	6.68E-2	6.68E-2	6.68E-2	6.68E-2	1	1.65	(3,4,5,3,3,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	4.15E-2	4.15E-2	4.15E-2	4.15E-2	1	1.65	(3,4,5,3,3,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	ceramic tiles, at regional storage	CH	0	kg	1.67E-1	1.67E-1	1.67E-1	1.67E-1	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	lime, hydrated, packed, at plant	CH	0	kg	2.22E-2	2.22E-2	2.22E-2	2.22E-2	1	1.65	(3,4,5,3,3,5); waste water treatment, Hagedorn 1992
	electricity, medium voltage, at grid	CN	0	kWh	3.20E+1	0	0	0	1	1.22	(2,2,1,2,1,5); ITRPV 2020, Fig. 6, p.9
	electricity, medium voltage, at grid	US	0	kWh	0	3.20E+1	0	0	1	1.22	(2,2,1,2,1,5); ITRPV 2020, Fig. 6, p.9
	electricity, medium voltage, at grid	KR	0	kWh	0	0	3.20E+1	0	1	1.22	(2,2,1,2,1,5); ITRPV 2020, Fig. 6, p.9
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	3.20E+1	1	1.22	(2,2,1,2,1,5); ITRPV 2020, Fig. 6, p.9
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	6.82E+1	6.82E+1	6.82E+1	6.82E+1	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	water, deionised, water balance according to MoeK 2013, at plant	CN	0	kg	4.01E+0	0	0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	water, deionised, water balance according to MoeK 2013, at plant	US	0	kg	0	4.01E+0	0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	water, deionised, water balance according to MoeK 2013, at plant	KR	0	kg	0	0	4.01E+0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	water, deionised, water balance according to MoeK 2013, at plant	RER	0	kg	0	0	0	4.01E+0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
resource, in water	Water, cooling, unspecified natural origin, CN	-	-	m3	5.09E+0	0	0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	Water, cooling, unspecified natural origin, US	-	-	m3	0	5.09E+0	0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	Water, cooling, unspecified natural origin, KR	-	-	m3	0	0	5.09E+0	0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	Water, cooling, unspecified natural origin, RER	-	-	m3	0	0	0	5.09E+0	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
transport	transport, freight, lorry, fleet average	RER	0	tkm	1.13E+0	1.13E+0	1.13E+0	1.13E+0	1	2.09	(4,5,na,na,na,na); Transport distance: 100km; silicon: 1000km
	transport, freight, rail	RER	0	tkm	1.41E+0	1.41E+0	1.41E+0	1.41E+0	1	2.09	(4,5,na,na,na,na); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
infrastructure	silicone plant	RER	1	unit	1.00E-11	1.00E-11	1.00E-11	1.00E-11	1	3.09	(1,2,4,1,3,3); Estimation
disposal	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	1.67E-1	1.67E-1	1.67E-1	1.67E-1	1	1.32	(1,4,4,2,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	4.84E+0	4.84E+0	4.84E+0	4.84E+0	1	1.63	(4,3,5,3,1,5); Calculation based on water withdrawal and water emissions
emission air	Heat, waste	-	-	MJ	1.15E+2	1.15E+2	1.15E+2	1.15E+2	1	1.58	(3,3,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	Water, CN	-	-	kg	2.55E+2	0	0	0	1	1.88	(4,3,5,3,1,5); Assumption: 5% evaporation of cooling water, 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, US	-	-	kg	0	2.55E+2	0	0	1	1.88	(4,3,5,3,1,5); Assumption: 5% evaporation of cooling water, 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, KR	-	-	kg	0	0	2.55E+2	0	1	1.88	(4,3,5,3,1,5); Assumption: 5% evaporation of cooling water, 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, RER	-	-	kg	0	0	0	2.55E+2	1	1.88	(4,3,5,3,1,5); Assumption: 5% evaporation of cooling water, 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Nitrogen oxides	-	-	kg	3.39E-2	3.39E-2	3.39E-2	3.39E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
emission water, river	Hydroxide	-	-	kg	4.42E-3	4.42E-3	4.42E-3	4.42E-3	1	3.30	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)
	BOD5, Biological Oxygen Demand	-	-	kg	1.30E-1	1.30E-1	1.30E-1	1.30E-1	1	3.33	(5,4,4,1,1,5); Extrapolation for sum parameter
	COD, Chemical Oxygen Demand	-	-	kg	1.30E-1	1.30E-1	1.30E-1	1.30E-1	1	3.33	(5,4,4,1,1,5); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	4.05E-2	4.05E-2	4.05E-2	4.05E-2	1	3.33	(5,4,4,1,1,5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	4.05E-2	4.05E-2	4.05E-2	4.05E-2	1	3.33	(5,4,4,1,1,5); Extrapolation for sum parameter
	Nitrate	-	-	kg	8.35E-2	8.35E-2	8.35E-2	8.35E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (table 9)

D APPENDIX: D

Table 12: Unit process LCI data of the single- and multi-crystalline silicon wafer production in China (CN) and North America (US)

	Name	Location	InfrastructureProcess	Unit	single-Si wafer, photovoltaics, at plant	multi-Si wafer, at plant	single-Si wafer, photovoltaics, at plant	multi-Si wafer, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CN	CN	US	US			
	InfrastructureProcess				0	0	0	0			
	Unit				m2	m2	m2	m2			
product	single-Si wafer, photovoltaics, at plant	CN	0	m2	1	0	0	0			
	multi-Si wafer, at plant	CN	0	m2	0	1	0	0			
	single-Si wafer, photovoltaics, at plant	US	0	m2	0	0	1	0			
	multi-Si wafer, at plant	US	0	m2	0	0	0	1			
	single-Si wafer, photovoltaics, at plant	APAC	0	m2	0	0	0	0			
	multi-Si wafer, at plant	APAC	0	m2	0	0	0	0			
	single-Si wafer, photovoltaics, at plant	RER	0	m2	0	0	0	0			
	multi-Si wafer, at plant	RER	0	m2	0	0	0	0			
technosphere	CZ single crystalline silicon, photovoltaics, at plant	CN	0	kg	5.95E-1	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	CN	0	kg	0	6.35E-1	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	US	0	kg	0	0	5.95E-1	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	US	0	kg	0	0	0	6.35E-1	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	APAC	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	APAC	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	RER	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	RER	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	flat glass, uncoated, at plant	RER	0	kg	9.99E-3	4.08E-2	9.99E-3	4.08E-2	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.50E-2	1.50E-2	1.50E-2	1.50E-2	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	2.70E-3	2.70E-3	2.70E-3	2.70E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	acetic acid, 98% in H2O, at plant	RER	0	kg	3.90E-2	3.90E-2	3.90E-2	3.90E-2	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	dipropylene glycol monomethyl ether, at plant	RER	0	kg	3.00E-1	3.00E-1	3.00E-1	3.00E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	alkylbenzene sulfonate, linear, petrochemical, at plant	RER	0	kg	2.40E-1	2.40E-1	2.40E-1	2.40E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	acrylic binder, 34% in H2O, at plant	RER	0	kg	2.00E-3	3.85E-3	2.00E-3	3.85E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	brass, at plant	CH	0	kg	7.44E-3	7.44E-3	7.44E-3	7.44E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	chromium steel 18/8, at plant	RER	0	kg	1.51E-3	1.51E-3	1.51E-3	1.51E-3	1	1.32	(3,2,1,1,3,5); Proxy for diamond wire; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	wire drawing, steel	RER	0	kg	8.95E-3	8.95E-3	8.95E-3	8.95E-3	1	1.32	(3,2,1,1,3,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	electricity, medium voltage, at grid	CN	0	kWh	4.76E+0	5.56E+0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	4.76E+0	5.56E+0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	4.00E+0	4.00E+0	4.00E+0	4.00E+0	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
water	water, deionised, water balance according to MoeK 2013, at plant	CN	0	kg	5.56E+1	5.56E+1	0	0	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	US	0	kg	0	0	5.56E+1	5.56E+1	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	KR	0	kg	0	0	0	0	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	RER	0	kg	0	0	0	0	1	1.26	(3,4,2,3,1,5); China photovoltaic cell industry cleaner production evaluation index system
disposal	disposal, waste, silicon wafer production, 0% water, to underground deposit	DE	0	kg	1.10E-1	1.70E-1	1.10E-1	1.70E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	1.26	(3,4,2,3,1,5); Calculation based on water withdrawal and water emissions
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.36E-1	2.77E-1	2.36E-1	2.77E-1	1	2.09	(4,5,na,na,na,na); Transport distance: 100km; silicon: 200km
	transport, freight, rail	RER	0	tkm	1.25E+0	1.27E+0	1.25E+0	1.27E+0	1	2.09	(4,5,na,na,na,na); Transport distance: 100-600km
infrastructure	wafer factory	DE	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	1	3.05	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
emission air	Heat, waste	-	-	MJ	1.71E+1	2.00E+1	1.71E+1	2.00E+1	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, CN	-	-	kg	5.56E+0	5.56E+0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, US	-	-	kg	0	0	5.56E+0	5.56E+0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, KR	-	-	kg	0	0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, RER	-	-	kg	0	0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
emission water, river	COD, Chemical Oxygen Demand	-	-	kg	2.95E-2	2.95E-2	2.95E-2	2.95E-2	1	1.64	(2,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	BOD5, Biological Oxygen Demand	-	-	kg	2.95E-2	2.95E-2	2.95E-2	2.95E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	COD, Chemical Oxygen Demand	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	TOC, Total Organic Carbon	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)

D APPENDIX: D

Table 13: Unit process LCI data of the single- and multi-crystalline silicon wafer production in Europe (RER) and Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	single-Si wafer, photovoltaics, at plant	multi-Si wafer, at plant	single-Si wafer, photovoltaics, at plant	multi-Si wafer, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				APAC	APAC	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				m2	m2	m2	m2			
product	single-Si wafer, photovoltaics, at plant	CN	0	m2	0	0	0	0			
	multi-Si wafer, at plant	CN	0	m2	0	0	0	0			
	single-Si wafer, photovoltaics, at plant	US	0	m2	0	0	0	0			
	multi-Si wafer, at plant	US	0	m2	0	0	0	0			
	single-Si wafer, photovoltaics, at plant	APAC	0	m2	1	0	0	0			
	multi-Si wafer, at plant	APAC	0	m2	0	1	0	0			
	single-Si wafer, photovoltaics, at plant	RER	0	m2	0	0	1	0			
	multi-Si wafer, at plant	RER	0	m2	0	0	0	1			
technosphere	CZ single crystalline silicon, photovoltaics, at plant	CN	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	CN	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	US	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	US	0	kg	0	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	APAC	0	kg	5.95E-1	0	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	APAC	0	kg	0	6.35E-1	0	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	CZ single crystalline silicon, photovoltaics, at plant	RER	0	kg	0	0	5.95E-1	0	1	1.22	(2,2,1,2,1,5); Wafer thickness: 170 um, kerf loss: 65 um, additional losses: 20.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	silicon, multi-Si, casted, at plant	RER	0	kg	0	0	0	6.35E-1	1	1.22	(2,2,1,2,1,5); Wafer thickness: 180 um, kerf loss: 65 um, additional losses: 27.5 um; silicon density: 2330 kg/m3; ITRPV 2020; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	flat glass, uncoated, at plant	RER	0	kg	9.99E-3	4.08E-2	9.99E-3	4.08E-2	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.50E-2	1.50E-2	1.50E-2	1.50E-2	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	2.70E-3	2.70E-3	2.70E-3	2.70E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	acetic acid, 98% in H2O, at plant	RER	0	kg	3.90E-2	3.90E-2	3.90E-2	3.90E-2	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	dipropylene glycol monomethyl ether, at plant	RER	0	kg	3.00E-1	3.00E-1	3.00E-1	3.00E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	alkylbenzene sulfonate, linear, petrochemical, at plant	RER	0	kg	2.40E-1	2.40E-1	2.40E-1	2.40E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	acrylic binder, 34% in H2O, at plant	RER	0	kg	3.85E-3	3.85E-3	2.00E-3	3.85E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	brass, at plant	CH	0	kg	7.44E-3	7.44E-3	7.44E-3	7.44E-3	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	chromium steel 18/8, at plant	RER	0	kg	1.51E-3	1.51E-3	1.51E-3	1.51E-3	1	1.32	(3,2,1,1,3,5); Proxy for diamond wire; Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	wire drawing, steel	RER	0	kg	8.95E-3	8.95E-3	8.95E-3	8.95E-3	1	1.32	(3,2,1,1,3,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	electricity, medium voltage, at grid	CN	0	kWh	0	0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	4.76E+0	5.56E+0	0	0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	4.76E+0	5.56E+0	1	2.05	(2,2,1,2,1,5); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	4.00E+0	4.00E+0	4.00E+0	4.00E+0	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
water	water, deionised, water balance according to MoeK 2013, at plant	CN	0	kg	0	0	0	0	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	US	0	kg	0	0	0	0	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	KR	0	kg	5.56E+1	5.56E+1	0	0	1	1.26	(3,4,2,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	water, deionised, water balance according to MoeK 2013, at plant	RER	0	kg	0	0	5.56E+1	5.56E+1	1	1.26	(3,4,2,3,1,5); China photovoltaic cell industry cleaner production evaluation index system
disposal	disposal, waste, silicon wafer production, 0% water, to underground deposit	DE	0	kg	1.70E-1	1.70E-1	1.10E-1	1.70E-1	1	1.22	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	1.26	(3,4,2,3,1,5); Calculation based on water withdrawal and water emissions
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.36E-1	2.77E-1	2.36E-1	2.77E-1	1	2.09	(4,5,na,na,na,na); Transport distance: 100km; silicon: 200km
	transport, freight, rail	RER	0	tkm	1.25E+0	1.27E+0	1.25E+0	1.27E+0	1	2.09	(4,5,na,na,na,na); Transport distance: 100-600km
infrastructure	wafer factory	DE	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	1	3.05	(1,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
emission air	Heat, waste	-	-	MJ	1.71E+1	2.00E+1	1.71E+1	2.00E+1	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, CN	-	-	kg	0	0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, US	-	-	kg	0	0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, KR	-	-	kg	5.56E+0	5.56E+0	0	0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	Water, RER	-	-	kg	0	0	5.56E+0	5.56E+0	1	1.65	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
emission water, river	COD, Chemical Oxygen Demand	-	-	kg	2.95E-2	2.95E-2	2.95E-2	2.95E-2	1	1.64	(2,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	BOD5, Biological Oxygen Demand	-	-	kg	2.95E-2	2.95E-2	2.95E-2	2.95E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	COD, Chemical Oxygen Demand	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)
	TOC, Total Organic Carbon	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 19,25)

Table 14 shows the unit process data of the silicon wafer market mixes in Europe (RER), North America (US) and Asia & Pacific (APAC). The values correspond to the shares given in Tab. 3.1.2.2. The transport distances with freight ships depend on the world region. Distances of 19’994 km, 20’755 km and 4584 km are assumed for the transport from China (Shanghai) to Europe (Rotterdam), from China (Shanghai) to North America (New York) and from China (Shanghai) to APAC (Port Klang), respectively. Furthermore, 50 km transport by lorry and 200 km transport by train are assumed independent of the region.

D APPENDIX: D

Table 16: Unit process data of the photovoltaic cell production in China (CN) and North America (US)

	Name	Location	InfrastructureProcess	Unit	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CN	CN	US	US			
	InfrastructureProcess				0	0	0	0			
	Unit				m2	m2	m2	m2			
product	photovoltaic cell, single-Si, at plant	CN	0	m2	1	0	0	0			
	photovoltaic cell, multi-Si, at plant	CN	0	m2	0	1	0	0			
	photovoltaic cell, single-Si, at plant	US	0	m2	0	0	1	0			
	photovoltaic cell, multi-Si, at plant	US	0	m2	0	0	0	1			
	photovoltaic cell, single-Si, at plant	APAC	0	m2	0	0	0	0			
	photovoltaic cell, multi-Si, at plant	APAC	0	m2	0	0	0	0			
	photovoltaic cell, single-Si, at plant	RER	0	m2	0	0	0	0			
	photovoltaic cell, multi-Si, at plant	RER	0	m2	0	0	0	0			
wafers	single-Si wafer, photovoltaics, at plant	CN	0	m2	1.03E+0	0	0	0	1	1.10	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at plant	CN	0	m2	0	1.04E+0	0	0	1	1.10	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	US	0	m2	0	0	1.03E+0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	US	0	m2	0	0	0	1.04E+0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	APAC	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	APAC	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	RER	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	RER	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
materials	metallization paste, front side, at plant	RER	0	kg	3.37E-3	3.37E-3	3.37E-3	3.37E-3	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	metallization paste, back side, at plant	RER	0	kg	1.11E-3	1.11E-3	1.11E-3	1.11E-3	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	metallization paste, back side, aluminium, at plant	RER	0	kg	5.54E-2	5.54E-2	5.54E-2	5.54E-2	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
chemicals	ammonia, liquid, at regional storehouse	RER	0	kg	2.19E-2	8.92E-3	2.19E-2	8.92E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	phosphoric acid, fertiliser grade, 70% in H2O, at plant	GLO	0	kg	0	8.63E-3	0	8.63E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	phosphoryl chloride, at plant	RER	0	kg	1.33E-2	2.74E-2	1.33E-2	2.74E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	isopropanol, at plant	RER	0	kg	1.77E-1	8.10E-4	1.77E-1	8.10E-4	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	solvents, organic, unspecified, at plant	GLO	0	kg	0	1.13E-2	0	1.13E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	calcium chloride, CaCl2, at regional storage	CH	0	kg	0	3.15E-2	0	3.15E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	6.29E-4	8.59E-3	6.29E-4	8.59E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrogen fluoride, at plant	GLO	0	kg	6.45E-4	4.03E-1	6.45E-4	4.03E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	nitric acid, 50% in H2O, at plant	RER	0	kg	0	2.93E-1	0	2.93E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	6.04E-1	7.07E-2	6.04E-1	7.07E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	lime, hydrated, packed, at plant	CH	0	kg	1.51E-2	2.18E-1	1.51E-2	2.18E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	0	4.52E-4	0	4.52E-4	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	sulphuric acid, liquid, at plant	RER	0	kg	0	1.01E-1	0	1.01E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	refrigerant R134a, at plant	RER	0	kg	3.12E-5	2.73E-5	3.12E-5	2.73E-5	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	potassium hydroxide, at regional storage	RER	0	kg	0	3.00E-2	0	3.00E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	0	2.10E-2	0	2.10E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
gases	oxygen, liquid, at plant	RER	0	kg	0	8.22E-3	0	8.22E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	nitrogen, liquid, at plant	RER	0	kg	1.15E+0	1.35E+0	1.15E+0	1.35E+0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	silane, at plant	RER	0	kg	2.91E-3	2.61E-3	2.91E-3	2.61E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	CN	0	kg	1.71E+2	2.51E+2	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	US	0	kg	0	0	1.71E+2	2.51E+2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	KR	0	kg	0	0	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	RER	0	kg	0	0	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
energy	electricity, medium voltage, at grid	CN	0	kWh	1.77E+1	1.77E+1	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	1.77E+1	1.77E+1	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	6.08E-2	2.47E-1	6.08E-2	2.47E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	0	2.70E-3	0	2.70E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
infrastructure	photovoltaic cell factory	DE	1	unit	4.00E-7	4.00E-7	4.00E-7	4.00E-7	1	3.05	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.74E-1	5.22E-1	2.74E-1	5.22E-1	1	2.09	(4,5,na,na,na,na); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	transport, freight, rail	RER	0	tkm	1.52E+0	3.94E-1	1.52E+0	3.94E-1	1	2.09	(4,5,na,na,na,na); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
disposal	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	1.54E-1	2.26E-1	1.54E-1	2.26E-1	1	1.22	(2,2,4,1,1,3); Calculation based on water withdrawal and water emissions
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	2.33E+0	2.74E+0	2.33E+0	2.74E+0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	disposal, solvents mixture, 16.5% water, to hazardous waste incineration	CH	0	kg	1.72E-1	1.08E-2	1.72E-1	1.08E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
emission air, high population density	Heat, waste	-	-	MJ	5.18E+1	5.18E+1	5.18E+1	5.18E+1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Water, CN	-	-	kg	1.71E+1	2.51E+1	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, US	-	-	kg	0	0	1.71E+1	2.51E+1	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, KR	-	-	kg	0	0	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, RER	-	-	kg	0	0	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Aluminium	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Hydrogen fluoride	-	-	kg	1.38E-4	6.90E-4	1.38E-4	6.90E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Lead	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	3.17E-8	3.17E-8	3.17E-8	3.17E-8	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silver	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Tin	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Ammonia	-	-	kg	3.73E-5	5.22E-4	3.73E-5	5.22E-4	1	1.31	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Carbon dioxide, fossil	-	-	kg	1.67E-1	6.82E-1	1.67E-1	6.82E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Chlorine	-	-	kg	4.60E-5	0	4.60E-5	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Hydrogen	-	-	kg	1.10E-2	4.44E-4	1.10E-2	4.44E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	2-Propanol	-	-	kg	1.47E-2	0	1.47E-2	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Acetaldehyde	-	-	kg	6.33E-4	0	6.33E-4	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	-	-	kg	3.12E-5	2.73E-5	3.12E-5	2.73E-5	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	3.33E-4	1.47E-4	3.33E-4	1.47E-4	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	2.63E-3	6.00E-6	2.63E-3	6.00E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.26E-2	3.53E-4	1.26E-2	3.53E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitric acid	-	-	kg	0	1.19E-4	0	1.19E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitrogen oxides	-	-	kg	0	1.24E-2	0	1.24E-2	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitrogen oxides	-	-	kg	0	3.64E-3	0	3.64E-3	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)

D APPENDIX: D

Table 17: Unit process LCA data of the photovoltaic cell production in Europe (RER) and Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				APAC	APAC	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				m2	m2	m2	m2			
product	photovoltaic cell, single-Si, at plant	CN	0	m2	0	0	0	0			
	photovoltaic cell, multi-Si, at plant	CN	0	m2	0	0	0	0			
	photovoltaic cell, single-Si, at plant	US	0	m2	0	0	0	0			
	photovoltaic cell, multi-Si, at plant	US	0	m2	0	0	0	0			
	photovoltaic cell, single-Si, at plant	APAC	0	m2	1	0	0	0			
	photovoltaic cell, multi-Si, at plant	APAC	0	m2	0	1	0	0			
	photovoltaic cell, single-Si, at plant	RER	0	m2	0	0	1	0			
	photovoltaic cell, multi-Si, at plant	RER	0	m2	0	0	0	1			
wafers	single-Si wafer, photovoltaics, at plant	CN	0	m2	0	0	0	0	1	1.10	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at plant	CN	0	m2	0	0	0	0	1	1.10	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	US	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	US	0	m2	0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	APAC	0	m2	1.03E+0	0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	APAC	0	m2	0	1.04E+0	0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	single-Si wafer, photovoltaics, at regional storage	RER	0	m2	0	0	1.03E+0	0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	multi-Si wafer, at regional storage	RER	0	m2	0	0	0	1.04E+0	1	3.01	(2,2,2,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
materials	metallization paste, front side, at plant	RER	0	kg	3.37E-3	3.37E-3	3.37E-3	3.37E-3	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	metallization paste, back side, at plant	RER	0	kg	1.11E-3	1.11E-3	1.11E-3	1.11E-3	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	metallization paste, back side, aluminium, at plant	RER	0	kg	5.54E-2	5.54E-2	5.54E-2	5.54E-2	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
chemicals	ammonia, liquid, at regional storehouse	RER	0	kg	2.19E-2	8.92E-3	2.19E-2	8.92E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	phosphoric acid, fertiliser grade, 70% in H2O, at plant	GLO	0	kg	0	8.63E-3	0	8.63E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	phosphoryl chloride, at plant	RER	0	kg	1.33E-2	2.74E-2	1.33E-2	2.74E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	isopropanol, at plant	RER	0	kg	1.77E-1	8.10E-4	1.77E-1	8.10E-4	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	solvents, organic, unspecified, at plant	GLO	0	kg	0	1.13E-2	0	1.13E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	calcium chloride, CaCl2, at regional storage	CH	0	kg	0	3.15E-2	0	3.15E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	6.29E-4	8.59E-3	6.29E-4	8.59E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrogen fluoride, at plant	GLO	0	kg	6.45E-4	4.03E-1	6.45E-4	4.03E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	nitric acid, 50% in H2O, at plant	RER	0	kg	0	2.93E-1	0	2.93E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	6.04E-1	7.07E-2	6.04E-1	7.07E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	lime, hydrated, packed, at plant	CH	0	kg	1.51E-2	2.18E-1	1.51E-2	2.18E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	0	4.52E-4	0	4.52E-4	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	sulphuric acid, liquid, at plant	RER	0	kg	0	1.01E-1	0	1.01E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	refrigerant R134a, at plant	RER	0	kg	3.12E-5	2.73E-5	3.12E-5	2.73E-5	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	potassium hydroxide, at regional storage	RER	0	kg	0	3.00E-2	0	3.00E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	0	2.10E-2	0	2.10E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
gases	oxygen, liquid, at plant	RER	0	kg	0	8.22E-3	0	8.22E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	nitrogen, liquid, at plant	RER	0	kg	1.15E+0	1.35E+0	1.15E+0	1.35E+0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	silane, at plant	RER	0	kg	2.91E-3	2.61E-3	2.91E-3	2.61E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	CN	0	kg	0	0	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	US	0	kg	0	0	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	KR	0	kg	1.71E+2	2.51E+2	0	0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	tap water, water balance according to MoeK 2013, at user	RER	0	kg	0	0	1.71E+2	2.51E+2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
energy	electricity, medium voltage, at grid	CN	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	1.77E+1	1.77E+1	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	1.77E+1	1.77E+1	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	6.08E-2	2.47E-1	6.08E-2	2.47E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	0	2.70E-3	0	2.70E-3	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
infrastructure	photovoltaic cell factory	DE	1	unit	4.00E-7	4.00E-7	4.00E-7	4.00E-7	1	3.05	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.74E-1	5.22E-1	2.74E-1	5.22E-1	1	2.09	(4,5,na,na,na,na); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	transport, freight, rail	RER	0	tkm	1.52E+0	3.94E-1	1.52E+0	3.94E-1	1	2.09	(4,5,na,na,na,na); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
disposal	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	1.54E-1	2.26E-1	1.54E-1	2.26E-1	1	1.22	(2,2,4,1,1,3); Calculation based on water withdrawal and water emissions
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	2.33E+0	2.74E+0	2.33E+0	2.74E+0	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	disposal, solvents mixture, 16.5% water, to hazardous waste incineration	CH	0	kg	1.72E-1	1.08E-2	1.72E-1	1.08E-2	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
emission air, high population density	Heat, waste	-	-	MJ	5.18E+1	5.18E+1	5.18E+1	5.18E+1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Water, CN	-	-	kg	0	0	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, US	-	-	kg	0	0	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, KR	-	-	kg	1.71E+1	2.51E+1	0	0	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Water, RER	-	-	kg	0	0	1.71E+1	2.51E+1	1	1.63	(2,3,4,3,1,5); Assumption: 10% evaporation of process water; Frischknecht & Büsser Knöpfel (2013)
	Aluminium	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Hydrogen fluoride	-	-	kg	1.38E-4	6.90E-4	1.38E-4	6.90E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Lead	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	3.17E-8	3.17E-8	3.17E-8	3.17E-8	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silver	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Tin	-	-	kg	7.73E-6	7.73E-6	7.73E-6	7.73E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Ammonia	-	-	kg	3.73E-5	5.22E-4	3.73E-5	5.22E-4	1	1.31	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Carbon dioxide, fossil	-	-	kg	1.67E-1	6.82E-1	1.67E-1	6.82E-1	1	1.22	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Chlorine	-	-	kg	4.60E-5	0	4.60E-5	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Hydrogen	-	-	kg	1.10E-2	4.44E-4	1.10E-2	4.44E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	2-Propanol	-	-	kg	1.47E-2	0	1.47E-2	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Acetaldehyde	-	-	kg	6.33E-4	0	6.33E-4	0	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	-	-	kg	3.12E-5	2.73E-5	3.12E-5	2.73E-5	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	3.33E-4	1.47E-4	3.33E-4	1.47E-4	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Silicon	-	-	kg	2.63E-3	6.00E-6	2.63E-3	6.00E-6	1	5.06	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.26E-2	3.53E-4	1.26E-2	3.53E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitric acid	-	-	kg	0	1.19E-4	0	1.19E-4	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitrogen oxides	-	-	kg	0	1.24E-2	0	1.24E-2	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)
	Nitrogen oxides	-	-	kg	0	3.64E-3	0	3.64E-3	1	1.57	(2,2,4,1,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 30,31)

D APPENDIX: D

Table 19: Unit process LCI data of the photovoltaic laminate and panel production in China (CN)

	Name	Location	InfrastructureProcess	Unit	photovoltaic panel, single-Si, at plant	photovoltaic panel, multi-Si, at plant	photovoltaic laminate, single-Si, at plant	photovoltaic laminate, multi-Si, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CN	CN	CN	CN			
	InfrastructureProcess				1	1	1	1			
	Unit				m2	m2	m2	m2			
product	photovoltaic panel, single-Si, at plant	CN	1	m2	1	0	0	0			
	photovoltaic panel, multi-Si, at plant	CN	1	m2	0	1	0	0			
	photovoltaic laminate, single-Si, at plant	CN	1	m2	0	0	1	0			
	photovoltaic laminate, multi-Si, at plant	CN	1	m2	0	0	0	1			
	photovoltaic panel, single-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	RER	1	m2	0	0	0	0			
materials	photovoltaic cell, single-Si, at plant	CN	0	m2	9.35E-1	0	9.35E-1	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	CN	0	m2	0	9.35E-1	0	9.35E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	US	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	US	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at plant	APAC	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	APAC	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	aluminium alloy, AlMg3, at plant	RER	0	kg	2.13E+0	2.13E+0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	copper, at regional storage	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	wire drawing, copper	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	diode, unspecified, at plant	GLO	0	kg	2.81E-3	2.81E-3	2.81E-3	2.81E-3	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	silicone product, at plant	RER	0	kg	1.22E-1	1.22E-1	1.22E-1	1.22E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tin, at regional storage	RER	0	kg	1.29E-2	1.29E-2	1.29E-2	1.29E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	lead, at regional storage	RER	0	kg	7.25E-4	7.25E-4	7.25E-4	7.25E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	solar glass, low-iron, at regional storage	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.33	(1,4,4,3,3,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tempering, flat glass	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	2.95E-1	2.95E-1	2.95E-1	2.95E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene terephthalate, granulate, amorphous, at plant	RER	0	kg	3.46E-1	3.46E-1	3.46E-1	3.46E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene, HDPE, granulate, at plant	RER	0	kg	2.38E-2	2.38E-2	2.38E-2	2.38E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	ethylvinylacetate, foil, at plant	RER	0	kg	8.75E-1	8.75E-1	8.75E-1	8.75E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyvinylfluoride film, at plant	US	0	kg	1.12E-1	1.12E-1	1.12E-1	1.12E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
auxiliaries	tap water, water balance according to MoeK 2013, at user	CN	0	kg	5.03E+0	5.03E+0	5.03E+0	5.03E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	US	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	KR	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	RER	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	hydrogen fluoride, at plant	GLO	0	kg	6.24E-2	6.24E-2	6.24E-2	6.24E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	1-propanol, at plant	RER	0	kg	1.59E-2	1.59E-2	1.59E-2	1.59E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	isopropanol, at plant	RER	0	kg	1.47E-4	1.47E-4	1.47E-4	1.47E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	potassium hydroxide, at regional storage	RER	0	kg	5.14E-2	5.14E-2	5.14E-2	5.14E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	soap, at plant	RER	0	kg	1.16E-2	1.16E-2	1.16E-2	1.16E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	7.63E-1	7.63E-1	7.63E-1	7.63E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	EUR-flat pallet	RER	0	unit	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
energy	electricity, medium voltage, at grid	CN	0	kWh	1.40E+1	1.40E+1	1.40E+1	1.40E+1	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	diesel, burned in building machine, average	CH	0	MJ	8.75E-3	8.75E-3	8.75E-3	8.75E-3	1	2.12	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.77E+0	3.01E+0	2.56E+0	2.79E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, cells 500km
	transport, freight, rail	RER	0	tkm	1.66E+1	1.66E+1	1.54E+1	1.54E+1	1	2.09	(4,5,na,na,na,na); Standard distance 600km
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	3.00E-2	3.00E-2	3.00E-2	1	1.24	(1,4,4,3,1,3); Alsema (personal communication) 2007, production waste
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	4.29E-3	4.29E-3	4.29E-3	4.29E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	2.81E-2	2.81E-2	2.81E-2	2.81E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.61E-3	1.61E-3	1.61E-3	1.61E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	4.53E-3	4.53E-3	4.53E-3	4.53E-3	1	1.24	(1,4,4,3,1,3); Calculation, water use
emissions air	Heat, waste	-	-	MJ	5.03E+1	5.03E+1	5.03E+1	5.03E+1	1	1.60	(3,4,5,3,1,5); Calculation, electricity use
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	8.06E-3	8.06E-3	8.06E-3	8.06E-3	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Carbon dioxide, fossil	-	-	kg	2.18E-2	2.18E-2	2.18E-2	2.18E-2	1	1.60	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, CN	-	-	kg	5.03E-1	5.03E-1	5.03E-1	5.03E-1	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, US	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, KR	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, RER	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)

D APPENDIX: D

Table 20: Unit process LCI data of the photovoltaic laminate and panel production in North America (US)

	Name	Location	InfrastructureProcess	Unit	photovoltaic panel, single-Si, at plant	photovoltaic panel, multi-Si, at plant	photovoltaic laminate, single-Si, at plant	photovoltaic laminate, multi-Si, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				US	US	US	US			
	InfrastructureProcess				1	1	1	1			
	Unit				m2	m2	m2	m2			
product	photovoltaic panel, single-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	US	1	m2	1	0	0	0			
	photovoltaic panel, multi-Si, at plant	US	1	m2	0	1	0	0			
	photovoltaic laminate, single-Si, at plant	US	1	m2	0	0	1	0			
	photovoltaic laminate, multi-Si, at plant	US	1	m2	0	0	0	1			
	photovoltaic panel, single-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	APAC	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	RER	1	m2	0	0	0	0			
materials	photovoltaic cell, single-Si, at plant	CN	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	CN	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	US	0	m2	9.35E-1	0	9.35E-1	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	US	0	m2	0	9.35E-1	0	9.35E-1	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at plant	APAC	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	APAC	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	aluminium alloy, AlMg3, at plant	RER	0	kg	2.13E+0	2.13E+0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	copper, at regional storage	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	wire drawing, copper	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	diode, unspecified, at plant	GLO	0	kg	2.81E-3	2.81E-3	2.81E-3	2.81E-3	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	silicone product, at plant	RER	0	kg	1.22E-1	1.22E-1	1.22E-1	1.22E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tin, at regional storage	RER	0	kg	1.29E-2	1.29E-2	1.29E-2	1.29E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	lead, at regional storage	RER	0	kg	7.25E-4	7.25E-4	7.25E-4	7.25E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	solar glass, low-iron, at regional storage	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.33	(1,4,4,3,3,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tempering, flat glass	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	2.95E-1	2.95E-1	2.95E-1	2.95E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene terephthalate, granulate, amorphous, at plant	RER	0	kg	3.46E-1	3.46E-1	3.46E-1	3.46E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene, HDPE, granulate, at plant	RER	0	kg	2.38E-2	2.38E-2	2.38E-2	2.38E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	ethylvinylacetate, foil, at plant	RER	0	kg	8.75E-1	8.75E-1	8.75E-1	8.75E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyvinylfluoride film, at plant	US	0	kg	1.12E-1	1.12E-1	1.12E-1	1.12E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
auxiliaries	tap water, water balance according to MoeK 2013, at user	CN	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	US	0	kg	5.03E+0	5.03E+0	5.03E+0	5.03E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	KR	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	RER	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	hydrogen fluoride, at plant	GLO	0	kg	6.24E-2	6.24E-2	6.24E-2	6.24E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	1-propanol, at plant	RER	0	kg	1.59E-2	1.59E-2	1.59E-2	1.59E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	isopropanol, at plant	RER	0	kg	1.47E-4	1.47E-4	1.47E-4	1.47E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	potassium hydroxide, at regional storage	RER	0	kg	5.14E-2	5.14E-2	5.14E-2	5.14E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	soap, at plant	RER	0	kg	1.16E-2	1.16E-2	1.16E-2	1.16E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	7.63E-1	7.63E-1	7.63E-1	7.63E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	EUR-flat pallet	RER	0	unit	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
energy	electricity, medium voltage, at grid	CN	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	1.40E+1	1.40E+1	1.40E+1	1.40E+1	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	diesel, burned in building machine, average	CH	0	MJ	8.75E-3	8.75E-3	8.75E-3	8.75E-3	1	2.12	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.99E+0	3.01E+0	2.78E+0	2.79E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, cells 500km
	transport, freight, rail	RER	0	tkm	1.66E+1	1.66E+1	1.54E+1	1.54E+1	1	2.09	(4,5,na,na,na,na); Standard distance 600km
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	3.00E-2	3.00E-2	3.00E-2	1	1.24	(1,4,4,3,1,3); Alsema (personal communication) 2007, production waste
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	4.29E-3	4.29E-3	4.29E-3	4.29E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	2.81E-2	2.81E-2	2.81E-2	2.81E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.61E-3	1.61E-3	1.61E-3	1.61E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	4.53E-3	4.53E-3	4.53E-3	4.53E-3	1	1.24	(1,4,4,3,1,3); Calculation, water use
emissions air	Heat, waste	-	-	MJ	5.03E+1	5.03E+1	5.03E+1	5.03E+1	1	1.60	(3,4,5,3,1,5); Calculation, electricity use
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	8.06E-3	8.06E-3	8.06E-3	8.06E-3	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Carbon dioxide, fossil	-	-	kg	2.18E-2	2.18E-2	2.18E-2	2.18E-2	1	1.60	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, CN	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, US	-	-	kg	5.03E-1	5.03E-1	5.03E-1	5.03E-1	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, KR	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, RER	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)

D APPENDIX: D

Table 21: Unit process LCI data of the photovoltaic laminate and panel production in Asia & Pacific (APAC)

	Name	Location	InfrastructureProcess	Unit	photovoltaic panel, single-Si, at plant	photovoltaic panel, multi-Si, at plant	photovoltaic laminate, single-Si, at plant	photovoltaic laminate, multi-Si, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				APAC	APAC	APAC	APAC			
	InfrastructureProcess				1	1	1	1			
	Unit				m2	m2	m2	m2			
product	photovoltaic panel, single-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	CN	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	US	1	m2	0	0	0	0			
	photovoltaic panel, single-Si, at plant	APAC	1	m2	1	0	0	0			
	photovoltaic panel, multi-Si, at plant	APAC	1	m2	0	1	0	0			
	photovoltaic laminate, single-Si, at plant	APAC	1	m2	0	0	1	0			
	photovoltaic laminate, multi-Si, at plant	APAC	1	m2	0	0	0	1			
	photovoltaic panel, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic panel, multi-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, single-Si, at plant	RER	1	m2	0	0	0	0			
	photovoltaic laminate, multi-Si, at plant	RER	1	m2	0	0	0	0			
materials	photovoltaic cell, single-Si, at plant	CN	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	CN	0	m2	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	US	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	US	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at plant	APAC	0	m2	9.35E-1	0	9.35E-1	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at plant	APAC	0	m2	0	9.35E-1	0	9.35E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, single-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	photovoltaic cell, multi-Si, at regional storage	RER	0	m2	0	0	0	0	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	aluminium alloy, AlMg3, at plant	RER	0	kg	2.13E+0	2.13E+0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	copper, at regional storage	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	wire drawing, copper	RER	0	kg	1.03E-1	1.03E-1	1.03E-1	1.03E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	diode, unspecified, at plant	GLO	0	kg	2.81E-3	2.81E-3	2.81E-3	2.81E-3	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	silicone product, at plant	RER	0	kg	1.22E-1	1.22E-1	1.22E-1	1.22E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tin, at regional storage	RER	0	kg	1.29E-2	1.29E-2	1.29E-2	1.29E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	lead, at regional storage	RER	0	kg	7.25E-4	7.25E-4	7.25E-4	7.25E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	solar glass, low-iron, at regional storage	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.33	(1,4,4,3,3,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tempering, flat glass	RER	0	kg	8.81E+0	8.81E+0	8.81E+0	8.81E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	2.95E-1	2.95E-1	2.95E-1	2.95E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene terephthalate, granulate, amorphous, at plant	RER	0	kg	3.46E-1	3.46E-1	3.46E-1	3.46E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyethylene, HDPE, granulate, at plant	RER	0	kg	2.38E-2	2.38E-2	2.38E-2	2.38E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	ethylvinylacetate, foil, at plant	RER	0	kg	8.75E-1	8.75E-1	8.75E-1	8.75E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	polyvinylfluoride film, at plant	US	0	kg	1.12E-1	1.12E-1	1.12E-1	1.12E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
auxiliaries	tap water, water balance according to MoeK 2013, at user	CN	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	US	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	KR	0	kg	5.03E+0	5.03E+0	5.03E+0	5.03E+0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	tap water, water balance according to MoeK 2013, at user	RER	0	kg	0	0	0	0	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	hydrogen fluoride, at plant	GLO	0	kg	6.24E-2	6.24E-2	6.24E-2	6.24E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	1-propanol, at plant	RER	0	kg	1.59E-2	1.59E-2	1.59E-2	1.59E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	isopropanol, at plant	RER	0	kg	1.47E-4	1.47E-4	1.47E-4	1.47E-4	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	potassium hydroxide, at regional storage	RER	0	kg	5.14E-2	5.14E-2	5.14E-2	5.14E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	soap, at plant	RER	0	kg	1.16E-2	1.16E-2	1.16E-2	1.16E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	7.63E-1	7.63E-1	7.63E-1	7.63E-1	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	EUR-flat pallet	RER	0	unit	5.00E-2	5.00E-2	5.00E-2	5.00E-2	1	1.34	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
energy	electricity, medium voltage, at grid	CN	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	US	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, at grid	KR	0	kWh	1.40E+1	1.40E+1	1.40E+1	1.40E+1	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	0	0	0	0	1	1.09	(2,2,1,1,1,3); Woodhouse et al. (2019): c-Si PV Manufacturing Costs 2018
	diesel, burned in building machine, average	CH	0	MJ	8.75E-3	8.75E-3	8.75E-3	8.75E-3	1	2.12	(3,4,4,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	1	3.06	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
transport	transport, freight, lorry, fleet average	RER	0	tkm	2.99E+0	3.01E+0	2.78E+0	2.79E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, cells 500km
	transport, freight, rail	RER	0	tkm	1.66E+1	1.66E+1	1.54E+1	1.54E+1	1	2.09	(4,5,na,na,na,na); Standard distance 600km
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	3.00E-2	3.00E-2	3.00E-2	1	1.24	(1,4,4,3,1,3); Alsema (personal communication) 2007, production waste
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	4.29E-3	4.29E-3	4.29E-3	4.29E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	2.81E-2	2.81E-2	2.81E-2	2.81E-2	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.61E-3	1.61E-3	1.61E-3	1.61E-3	1	1.24	(1,4,4,3,1,3); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	4.53E-3	4.53E-3	4.53E-3	4.53E-3	1	1.24	(1,4,4,3,1,3); Calculation, water use
emissions air	Heat, waste	-	-	MJ	5.03E+1	5.03E+1	5.03E+1	5.03E+1	1	1.60	(3,4,5,3,1,5); Calculation, electricity use
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	8.06E-3	8.06E-3	8.06E-3	8.06E-3	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Carbon dioxide, fossil	-	-	kg	2.18E-2	2.18E-2	2.18E-2	2.18E-2	1	1.60	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, CN	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, US	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, KR	-	-	kg	5.03E-1	5.03E-1	5.03E-1	5.03E-1	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)
	Water, RER	-	-	kg	0	0	0	0	1	1.85	(3,4,5,3,1,5); de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection (Table 37)

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