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The Environmental and Social Impacts of Single Crystalline Silicon Photovoltaic Modules

Roelofs, Jan L.T.

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The Environmental and Social Impacts of Single Crystalline Silicon Photovoltaic Modules

Roelofs, J.L.T.

Student ID: 1493256

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Thesis supervisor:

prof. dr. Alkemade, F.	Industrial Engineering and Innovation Sciences - TU/e

Thesis committee:

dr. Hauck, M.	Industrial Engineering and Innovation Sciences - TU/e
dr.ir. Loonen, R.	Built Environment, TU/e

Company supervisor

Fu, L.	Group Procurement, IT, and ESG Director - Ecorus

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Name

Roelofs, J.L.T. ……………………………………………………..…………..

ID-number

1493256 ……………………………………………………..…………..

Signature

J. Roelofs ……………………………………………………..…………..

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Preface

This master thesis has been written in partial fulfilment of the requirements for the degree of the Master of Science in Sustainable Energy Technology at the technical university Eindhoven. I was engaged in researching and writing this master thesis from April to December 2022. I would like to evaluate this period by expressing my appreciation to some persons.

I want to start by expressing my sincere appreciation to the people at Ecorus. They offered me the chance to graduate at this growing company while also letting me broaden my professional experience. They trusted on my capabilities and embraced me into the procurement team. Then, as the Ecorus supervisors, I want to express my gratitude to Fubin and San for their strong support and guidance. During our weekly meeting, you always patiently discussed the details of the research with me, but also taught me a lot about what matters in business.

I also want to thank my lovely girlfriend, my friends, and my family for always being there for me. You gave me words of encouragement, reminded me to stay optimistic in the face of every challenge, and showed me that you believed in me, which helped me to believe in myself. I eagerly await new challenges and will use my tremendous passion to do everything in my power to help make our planet more sustainable.

Jan Roelofs
2 December 2022
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Summary

To combat climate change, the capacity of solar energy has been heavily incentivized in recent years. The International Energy Agency estimates that by 2021, there will be almost 1100 GW of photovoltaic (PV) capacity worldwide [1]. As the global PV market expands, it is expected that the supply chain of PV panels is getting under more pressure. This might be harmful to workers, as well as any other involved stakeholders but might also impact the environment. This is recognized by Cooperate Social Responsibility (CSR), which entails taking responsibility for a company's influence on the environment, society, employees, and animal welfare while pursuing economic success. This concept is likely to receive more attention and hence it is important that both the environmental and social performance of a PV module are carefully considered. Ecorus, the commissioner of this research, aims to establish a clear picture of the impacts of a PV module.

Objective

The main objective of this thesis study is to assess the environmental and social performance of the single crystalline silicon (sc-Si) PV module. Due to technological improvements in recent years, it was expected that an updated study that assesses environmental impacts was required. Also, since no attempts have been made to identify social impacts of a PV module, this research aimed to realize a first assessment that identifies these impacts. Based on these identifications, it was intended to conclude on the social and environmental hotspots. These hotspots can be defined as the stages within the life cycle that has the biggest contribution to the overall impacts. By addressing these problem areas, social conditions for the involved stakeholders can be improved and the environmental impact throughout the life cycle can be lowered. Furthermore, this study aims to support the development of the social life cycle assessment methodology by additional testing and suggesting possible refinements, resulting in a more robust methodology.

Methodology

This research applies an Environmental Life Cycle Assessment (E-LCA) and Social Life Cycle Assessment (S-LCA) to assess the environmental and social impacts associated with the sc-Si PV module. The LCA methodology generally consists of four steps: (1) goal and scope definition; (2) collection of Life Cycle Inventory data; (3) performing the Life Cycle Impact Assessment; and (4) interpretation of the results from previous steps. After the goal and scope were defined, the second step comprises the selection of the data in order to assess the social and environmental performances. The E-LCA is majorly drawn upon the inventory of Frischknecht et al. (2020), the Ecoinvent v3.8 database and obtained data from Ecorus [2]. The S-LCA used primarily inventory data from reports of internationally recognized institutions (e.g., the United Nations High Commissioner for Human Rights (OHCHR) and the Sheffield university) but also desk research and interviews were conducted to obtain the inventory data. Then, all inventory data is aggregated into impact categories to ensure effective communication. Last, these impact categories are interpreted and conclusions were drawn

in order to answer the research question.

Results and Conclusions

The supply chain for a typical solar PV module was first identified in order to assess the associated social and environmental impacts. Generally, the PV supply chain consists of six stages: (1) extracting high-grade quartz; (2) melting this quartz into metallurgical-grade silicon (MGS); (3) refining the MGS into polysilicon; (4) purifying the polysilicon into mono-grade ingots; (5) converting the ingots into thin wafers; (6) Converting the wafers into cells; and (7) interconnecting the cells and sandwiching the whole between glass and plastic sheet. This research identified that a typical solar PV module comes from China and this end-product contains solar components originating from the Chinese province of Xinjiang. Furthermore, this identification has also revealed that the MGS and polysilicon production plants heavily rely on cheap coal-fired electricity.

After this identification, this was evaluated based on social and environmental performances. This study showed that, compared to the assessment using the most recent inventory data, 8 out of the 18 considered impact categories were impacted with more than 5%. The E-LCA study also demonstrated that due to the high energy requirements for the manufacturing of polysilicon and ingots, these processes represent environmental hotspots. In addition, the majority of the impact categories were significantly influenced by the Chinese electricity mix, the production of aluminum frames, and the End of Life (EoL). Furthermore, The S-LCA showed that the main social hotspots are located during MGS and polysilicon production. Given that the majority of the MGS and polysilicon production take place in the Xinjiang region, companies (e.g., JA Solar) downstream in the supply chain run significant risks of having their supply chain impacted by Xinjiang forced labor. Indigenous people from the Xinjiang region are employed for so-called "labor programs" (The People's Republic of China (PRC) introduced these programs to alleviate poverty) imply clear indicators of human trafficking and forced labor. Based on the outcomes of the research, possibilities for future studies and recommendations for Ecorus are proposed.

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List of Abbreviations and Acronyms

ALCA Atributional Life Cycle Assessment

CF Characterization Factor

CLCA Consequential Life Cycle Assessment

CSR Coorporate Social Responsibility

EoL End of Life

E-LCA Environmental Life Cycle Assessment

FU Funtional Unit

IEA International Energy Agency

ILO International Labor Organization

ISO International Organization for Standardization

ILCD International Reference Life Cycle Data

LCIA Life Cycle Impact Assessment

LCI Life Cycle Inventory

PV Photovoltaic

PVPS Photovoltaic Power Systems Programme

sc-Si Single-Crystalline Silicon

SHDB Social Hotspot DataBase

S-LCA Social Life Cycle Assessment

SETAC Society of Environmental Toxicology and Chemistry

UNEP United Nations Environmental Programme

UNHR Universal Declaration of Human Rights

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Chapter 1

Introduction

Climate change poses a major threat to people's livelihoods, as well as to places, animals, and ecosystems. To combat climate change, the Paris Agreement was drafted, which is a legally binding international treaty on climate change. In line with this agreement, more renewables should be integrated into the electricity mix. Solar energy is a renewable energy source that is currently adopted extensively in the electricity mix. Although solar panels are not harmful for the environment during operation, these can emit greenhouse gas emissions when all life cycle stages are considered. Besides the evaluation of the environmental pillar, it is also crucial to consider possible social impacts of a solar panel. However, an updated consideration of the environmental pillar is required, while the social aspect is completed ignored from a life cycle perspective of a PV module. This research aims to fill this knowledge gap by identifying social and environmental impacts for all involved life cycle stages of the PV module.

To combat climate change, the capacity of solar energy has been heavily incentivized, which in turn leads to technological improvements and cost-competitiveness compared to traditional electricity technologies. The global operational PV capacity in 2021 increased to almost 1100 GW due to a capacity growth of 17% compared to 2020 [1]. The largest contribution comes from China, followed by the European Union, the USA, and Japan. This large market share of China is a result of advantageous purchase prices, in combination with high-quality assurances. Overall, even though the PV module can convert sunlight into electricity without releasing any emissions, the extraction of raw materials, manufacturing, and transport, or recycling of solar panels can result in an environmental impact.

As the global PV market expands, it is expected that the supply chain of PV panels is getting under more pressure. This might be harmful for workers as well as any other involved stakeholders. This is recognized by Cooperate Social Responsibility (CSR), which entails taking responsibility for a company's influence on the environment, society, employees, and animal welfare while pursuing economic success. Business activities can affect their own employees, but also workers in the supply chain, communities around their operations, as well as the final consumers of their products and services [12]. This denotes the importance of systematically identifying social impacts over the entire supply chain for all types of stakeholders.

The environmental and social impacts can be measured by an Environmental Life Cycle Assessment and Social Life Cycle Assessment, respectively. An E-LCA is a method for systematically identifying, quantifying, interpreting, and evaluating the environmental impacts in the life cycle of a product, function, or service [13]. This same methodology framework is used to assess social impacts. The S-LCA is a procedure for evaluating the social impacts of a product, function, or service along its life cycle on different stakeholders [14]. By addressing these impacts, social and environmental performances of a PV module can be improved. In addition, these identifications can provide Ecorus and can be used for their CSR report.

1.1 Ecorus

The Ecorus group is a vertically integrated company that focuses on financing, developing, engineering, building, operating, and maintaining PV solar installations. These core operations have been segmented into different business units, including Ecorus Home, Ecorus Development, Ecorus Business, and Ecorus projects. These business units have developed in total of 215 solar projects and realized 335 MW of solar capacity.

Ecorus Development

Ecorus development develops solar projects, for rooftop-mounted (e.g., logistical centers) and ground-mounted installations (e.g., solar parks). For this purpose, this business unit supports subsidy applications, electricity grid connection applications, soil analysis, roof and roof-construction analysis, guidance and support with insurance questions, sourcing of EPC contractors (Engineering, Procurement, Construction), financing options and maintenance solutions.

Ecorus Home

This business unit focuses on the residential market, and in particular the social housing cooperations. Throughout the whole of the Netherlands, Ecorus Home supports its customers with designs, project management, customer & inhabitant communication, procurement of materials, construction and long-term maintenance.

Ecorus Business

Providing small and medium-sized commercial buildings (e.g., supermarkets) with PV installations is the main focus of Ecorus Business. This means that the design, procurements, and building of the solar installations are included within the responsibilities of the business unit.

Ecorus Projects

Ecorus Projects is the second largest EPC contractor in the Dutch solar industry. This business unit engineers, procures, and constructs both rooftop projects and ground-mounted solar parks. The procurement department procures the materials directly from the suppliers and ensures that the highest quality standards are met. This research was conducted for the Ecorus Projects business group.

1.2 Review on Environmental LCA and Social LCA studies for PV modules

PV modules convert solar energy into electric energy without emitting any greenhouse gas emissions during operation. This research only considers the PV module and excludes the balance of system (BOS) (components that realize PV system, such as mounting system, inverter, or cables). Generally, the cells present in the PV modules can be classified into three generations: (1) first generation; (2) second generation; and (3) third generation (also called next generation). The first generation includes the traditional and most commonly recognized PV panels with single crystalline silicon (sc-Si) base structure, while the second generation is based on thin-film solar cells (e.g., amorphous silicon, cadmium sulfide) and third PV panels comprise the more innovative non-silicon based cell technologies (e.g., organic/semi-organic cells, perovskite cells) [15].

In 2021 the renewable power capacity increased with 290 gigawatts (GW) of which more than the half can be attributed to solar PV. According to the IEA forecasts, the global annual renewable energy capacity will grow on overage with roughly 305 GW per year between 2021 and 2026. This suggests an acceleration of 60% compared to renewable energy growth over the previous five years. It is expected that the dominant factors that contribute to this growth are wind energy and solar PV. Most of the PV modules are currently manufactured in China, apparent from a 80% share in word's module production [1].

The body of recent E-LCAs of sc-Si PV modules has been summarized by Müller et. al (2021). This summary illustrates the wide diversity of the methodological choices within the different LCA studies. This diversity can be attributed to variations in inventory data (such as electricity mixes, material consumption, and energy requirements), variations in system boundaries, and variations in operational parameters (such as solar irradiation conditions, lifetime, module efficiency) [13]. For example, the energy mix is heavily determined by the year the study was conducted, which varies from 2005 – 2018, and the considered country. In addition, over the years the module efficiency is also rapidly increased, apparent from ranging numbers from 14 – 16.4%, which also lead to varying E-LCA results. Also, the system boundaries vary among the studies; for example, *cradle to gate*, *cradle to grave*, and *cradle to use* are all different assumptions of the studies. The most recent E-LCA on a PV module was realized by Müller et al. (2020). They used the inventory provided by Frischknecht et al. (2020) in combination with Ecoinvent, a widely used database within the E-LCA community [2]. They assessed the environmental impacts based on the EU PEFCR impact categories per 1 kW_p. For example, they calculated that the impact on climate change for the considered PV module is equal to 810 kg CO_2 per kW_p. Another comprehensive summary of E-LCA case studies on grid-connected solar PV modules has been summarized by Muteri et al. (2020). This study indicated that the majority of the considered E-LCA studies are inconsistent in the chosen functional unit (FU), which is the studied subject, making it complex to compare the outcomes of the E-LCA studies. This difficulty is apparent from the chosen FU in the considered studies; examples of FU are 1.2 kW_p, 1kWh, 1kW, and "one 60-cell silicon".

Both the effect of technological improvements and the effect of the shift in manufacturing locations for different PV technologies have been researched by Stamford and Azapagic (2018) by using an E-LCA [16]. The expansion in the PV market has resulted in rapid technological improvements and a shift in manufacturing to China. To conclude on the environmental effect of technological improvement, this study used 2005 and 2015 data, while environmental impact based on the manufacturing location is calculated based on a European and a Chinese manufacturing case. This paper formulated two main conclusions: (1) technology advancements have reduced the environmental consequences by 45% on average; (2) the manufacturing shift to China has increased the environmental impacts by an average of 9 – 13%.

Bonilla-Alicea and Fu (2022) provided an overview of earlier research that has investigated social impacts of different renewable energy sources [11]. Based on this overview, four main observations were drawn by these authors. First, a significant variation in choices of the renewable energy systems was observed. Second, different contextual conditions may influence political, environmental, regulatory, and economic features that can consequently influence the results of the social assessment. Third, various frameworks were identified to examine the social impacts, such as the Framework for Integrated Sustainability Assessment and the Cumulative Social Effects Framework. For example, Kabir et. Al (2017) carried out a questionnaire-based survey study to identify the social impacts of a solar home system in rural areas [17]. The last observation is that the system boundary over the identified studies differs significantly; for example, some studies only consider the production phase, while others consider the complete life cycle.

Regarding social impact assessments of solar PV, several studies have been identified that aim to assess the socio-economic performances of PV modules [11], [17], [18], [19], [20]. For example, Bonilla-Alicea and Fu (2022) assessed the social impacts of rooftop solar panels during the EoL phase by using an S-LCA framework. This study qualitatively evaluated socio-economic impacts for several impact categories, such as child labor, health and safety, and equity. This study identified the most severe impact categories within the considered system boundaries. Furthermore, Traverso et. al (2012) assessed the manufacturing of PV modules based on impact categories, such as family benefits, working hours, and number, of accidents at work. On the contrary, Huang et al. (2017) quantitatively assessed the economic and social impacts of China's multi-crystalline PV modules production stages. The last identified study determined both positive and negative impacts of solar PV for impact categories, such as land use and landscape, infrastructure, and energy market [19].

1.3 Problem identification

The literature review revealed that regularly examining the social and environmental impacts from a life cycle perspective can have a complementing effect and enable one to accurately determine the extent of sustainability of a PV module. However, this review showed that the social impact of the PV module has only been investigated for a small part of the supply (e.g., during production or for the EoL phase). The E-LCA literature study shows that it is crucial to frequently update the assessments due to technology developments and new inventory datasets.

Based on the literature review, it can be observed that some initiatives are taken to assess the environmental and socio-economic impacts of PV modules. However, some shortcomings are identified in the literature:

Social and environmental assessment under same conditions is missing for PV module:

1. There is a lack of both an social assessment and environmental assessment for a PV module under the same conditions (e.g., LCA approach and system boundaries). Since sustainable development consists of both environmental and social considerations, addressing both pillars may result in a more accurately depicted image of sustainability. Many of the identified LCA studies use different approaches, choices, and assumptions. In the case of the E-LCA, many of the identified E-LCA studies use different LCA approaches, impact assessment methods, FUs, and system boundaries. Although a standardized LCA approach would be beneficial to compare results, this is unpractical since each approach is adopted based on the goal of

the assessment. This unpracticality was recognized by the IEA after which general guidelines were proposed which LCA practitioners could incorporate during the LCA study. In the case of the social assessment, the predefined goal of the study and author's decisions heavily determines the considered stakeholders, impact categories, subcategories, and the corresponding indicators. Also the assessment method, FU, and system boundaries vary among the identified social studies. In order to conclude on the degree of sustainability of the PV module, a social and environmental assessment that both use the same LCA approach and system boundaries would be promising.

More research on E-LCA is required:

1. In the field of solar technology, research and development have been incentivized in recent years which leads to the fact that much of the PV E-LCA literature becomes outdated very quickly. Also, many of the E-LCA studies used data is often gathered by using relatively old databases [16]. For example, Ecoinvent, one of the most widely used E-LCA database, is based on relatively old datasets. The electricity mix of China, Germany, and Europe is based on data from 2012, 2017, and 2017, respectively [21]. These outdated inventories may result in misleading and inaccurate results so an updated impact assessment can be valuable. Furthermore, the significant technological developments realized in recent years further denotes the importance of regularly updating the assessments as indicated in chapter 2. Moreover, a mismatch can also be detected between the current PV efficiency and the used efficiencies in the E-LCA studies. Current commercial PV modules are characterized by efficiencies ranging from 16 – to 22%, while the most recent identified E-LCA study uses a PV efficiency of 19.8% [13]. Illustratively, another recent E-LCA on an sc-Si PV module, conducted by Stamford and Azapagic (2018) examined a variety of environmental impacts of PV modules manufactured in China, based on inventory data from 2014 to 2016 [16]. Due to the rapidly expanding PV market and industry in China, regular evaluations of the present level of technology and manufacturing processes are required to offer state-of-the-art results.

2. Although a LCA implies to include all life cycle stages, some phases are unconsidered within the identified studies. For example, the installation stage is often neglected and the transport of the PV module is frequently only considered on a high-level.

More research on S-LCA is required:

1. Most S-LCA studies exclude the consideration of social impacts over the entire supply chain. Numerous studies have investigated the beneficial macroeconomic effects, which are indicated in Chapter 2. However, no research has been conducted to assess the social impacts of PV modules over the entire life cycle for all stakeholders (e.g., workers, society, customers) [22]. Neglecting this may result in severe situations for workers in developing countries since these workers are most vulnerable to endure poor labor conditions. To overcome this, the comprehensive consideration of the social performances of a product for the entire supply chain can result in a more complete image of potential social impacts of PV modules.

2. The S-LCA methodology should undergo substantial testing and refinement since this is still an emerging methodology. This methodology refinement also includes the adoption of giving voice to the affected stakeholders. It is crucial to incorporate and engage stakeholders in the study as much as possible. So although this methodology is at a level where it may produce first and preliminary results, more testing and refinement can enhance the development of a robust S-LCA.

In conclusion, the knowledge gap is that the social impact of a PV module is not determined yet for all stakeholders and that the environmental impact assessment should be updated due to technology advancements. This study aims to consistently carry out an S-LCA and E-LCA under the same system boundaries. By considering both pillars for all life cycle stages of the PV module, a more accurate conclusion can be can be drawn about the degree of sustainability.

1.4 Research questions

The previous section described the current E-LCA and S-LCA limitations of sc-Ci PV modules. This research intends to overcome these inadequate points. The adoption of the social impact from a life cycle perspective and the updating of the life cycle environmental impacts of a PV module lead to lead to the following research question:

What are the environmental and social impacts of a typical photovoltaics module?

The research question implies two related challenges. Namely, the research question indicates that both the environmental and the social impact should be calculated. Both these challenges are allocated to an individual sub-question. Before these impacts can be identified for all life cycle stages, the supply chain should first be mapped. The first sub-question addresses this challenge. These fractions of the research are represented by the following sub-questions:

SQ1 *How can a typical supply chain of a photovoltaic module be described?*

This sub-question provides input for sub-questiontwo and three by describing how the global supply chain can be characterized and which parties are involved. After this, the associated environmental impacts of the processes can be determined, as well as the social impacts related to stakeholders.

SQ3 *What are the social impacts of a PV module when considering the relevant stakeholders?*

By considering the involved stakeholders during the life cycle stages, it is intended to identify potential social impacts of the PV module.

SQ2 *What are the involved environmental impacts caused by a PV module?*

The environmental impact will be calculated by considering all emissions and interventions within the considered system boundary.

These research questions will be answered by following two methodologies, which are represented in Figure 1.1. This figure shows the most important research phases of the research. The research methodology will be described in more detail in Chapter 3. Then, the the typical supply chain of a PV module is presented in Chapter 4. Sub-question two and three are presented in Chapter Chapter 5 and Chapter 6, respectively. Finally, the report ends with conclusions and discussions in Chapter 7.

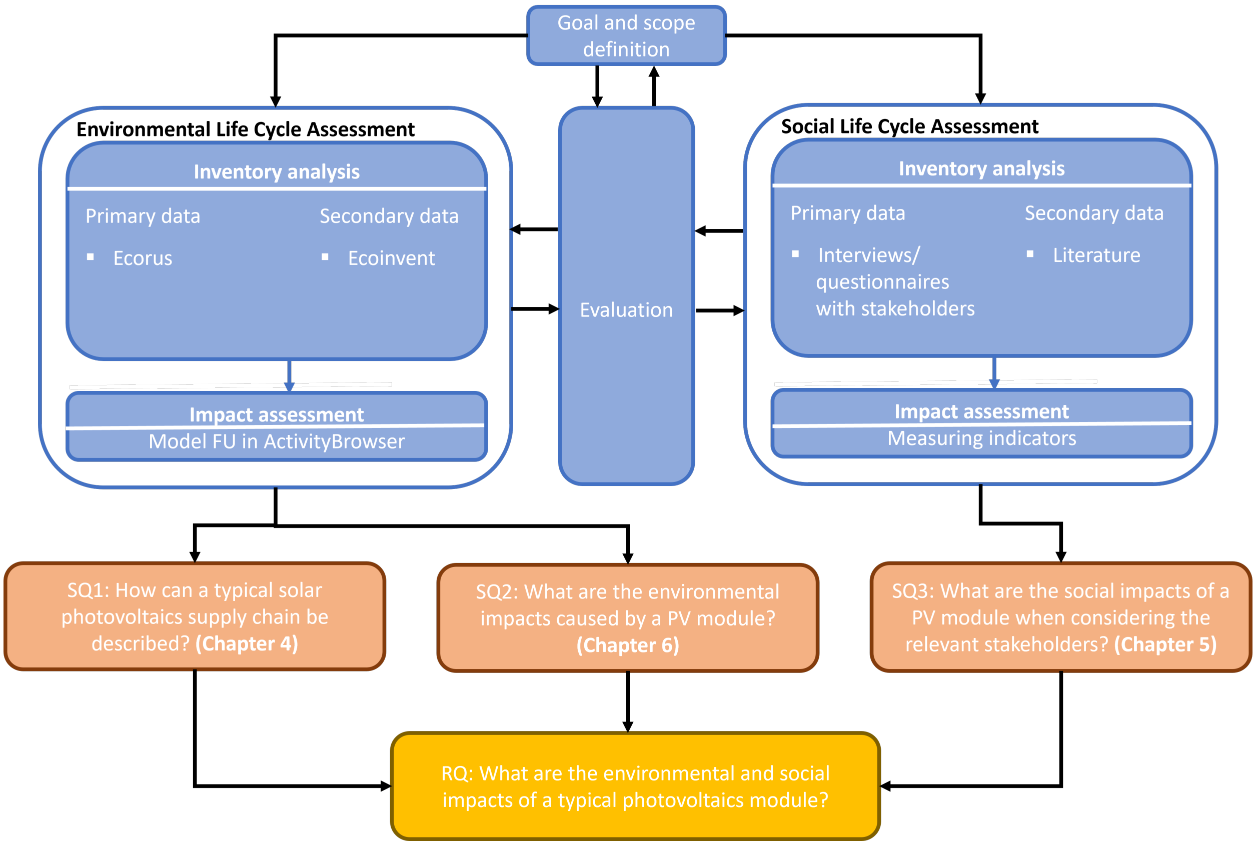


Figure 1.1: Research framework. Blue, orange, and yellow blocks represent LCA methodology, sub-questions, and main research question, respectively

The intended results of this research match with the desires of Ecorus, since the outcomes of this research can be used in the sustainability report that Ecorus wants to publish. Ecorus strives to gain insight into its supply chain and wants to assess this in terms of sustainability. This sustainability report allows Ecorus to justify itself in the field of corporate social responsibility.

Chapter 2

Literature Review

Considering the complete life cycle is crucial since although PV modules don't emit emissions during the operation phase, renewable energy technologies can produce harmful emissions or make use of scarce resources such as land, water and materials during other life cycle stages. A product's life cycle generally includes extracting and processing raw materials, manufacturing, operation, EoL management and is often distributed over diverse regions of the global economy. To obtain a comprehensive understanding of the social and environmental impacts of PV modules, a life cycle analytical methodology is required.

2.1 Methodology structure

The methodological framework of a LCA is visualized in Figure 2.1, and follows the general ISO 14040 and 14044 standards. This figure shows that the LCA framework contains the following steps: (1) define goal and scope; (2) plan and collect Life Cycle Inventory (LCI) data; (3) perform Life Cycle Impact Assessment (LCIA); and (4) interpret the results from previous steps. Furthermore, this method is characterized by an iterative nature, implying that repetition of all phases is applied in order to improve the accuracy and robustness of the results.

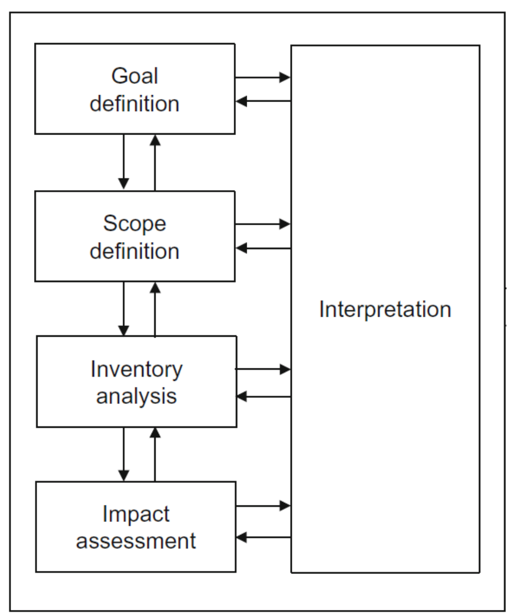


Figure 2.1: LCA framework according to ISO 14040 (taken from Hauschild et al. (2017) [3]

Step 1: Goal definition

The first phase of an LCA is formulating the main goal of the assessment. The overarching goal of LCAs is to produce results that can stimulate social and environmental performances of a product. According to the International Reference Life Cycle Data (ILCD) Handbook, six characteristics should be defined in the goal definition and these are explained in Table 2.1 [23].

Table 2.1: Goal definition - description of required items

Item	Explanation
Intended applications of the results	This step should clearly and unambiguously define the intended application of the study (e.g., comparing social/environmental impacts of several products or identifying parts in the life cycle where impacts are most significant = "hot spot identification").
Limitations due to methodological choices	Since methodological choices (e.g., impact categories, functional unit, system boundaries) can affect the LCA outcomes, it is necessary to state how that limits the interpretation of the results.
Decision context and reasons for carrying out the study	First, the rationale behind a study should be comprehended. This rationality should be directly related to the intended application of the study. It needs to be defined what the impact will be on the outcomes of the LCA. Generally, three different types of decision contexts can be recognized: (1) Situation A – in which the LCA results tend to support a decision but won't result in structural modifications; (2) Situation B – in which the study intends to support a decision, leading to structural modifications; and (3) Situation C – in which the study is entirely descriptive and is not intended to support any decision.
Target audience	Since the target audience may affect the level of detail that can be provided in the documentation, it is important to define this group.
Comparative studies to be disclosed to the public	This step should clearly define whether the LCA is characterized by a comparative nature and whether the results will be disclosed to the public. If this is the case, the ISO standards specify extra requirements to deal with these potential consequences.
Commissioner of the study and other influential actors	Since involved parties during the research might influence the study, it needs to be stated which parties are involved and how they potentially impact the LCA results due to their interests.

Step 2: Scope definition

The next stage is to define the scope of the project. Since the scope of a study defines what is included and excluded, it is required to adequately describe the scoping decisions. Ideally, the scope is defined such that the all potential impacts are identified within the entire supply chain. However, this scope is defined in such a way to ensure that the assessment is executable within the allotted time frame, but at the same time guarantees an acceptable level of detail. According to the ILCD Handbook, nine scoping items should be defined and their explanation is described in Table 2.2 [23].

Table 2.2: Scope definition - description of required items

Item	Explanation
Deliverables	In which the type of deliverable should be specified and should directly represent the intennded applications
Object of the assessment	In which the object and its function should be defined, as well as the functional unit.
LCI modeling framework and handling of multifunctional processes	Within the LCA community, two main types of LCA approaches can be recognized among many publications (more detailed information is provided in Chapter 2.2). This choice affects methodological choices, hence this choice should be argued reasonably. Also, it should be addressed how interacted systems or products are handled in this study.
System boundaries and completeness requirements	Specifying the system boundaries determines the unit processes which are included from which the social and environmental impacts are determined. Furthermore, the extent to which the impacts are captured in this study should be discussed.
Representativeness of LCI data	Although LCAs intend to represent reality, not all physical phenomena of the considered system can be included. Therefore this item seeks to conclude which LCI data can reflect reality.
Preparation of the basis for the impact assessment	This item emphasizes on considering how to perform the LCIA before starting with the LCIA. This can help in guaranteeing that appropriate data is gathered for the LCIA.
Special requirement for system comparisons	A requirements is proposed by the ILCD to prevent misleading LCA interpretations when comparing LCA studies.
Needs for critical review	A critical review of the LCA can contribute to ensuring the quality and credibility of the study. Therefore, in the scope definition it should be decided whether such a critical review will be incorporated.
Planning the reporting of results	Typically, three reporting levels can be recognized: (1) internal use; (2) external use by the third party; and (3) comparative studies to be disclosed to the public. The choice for selecting a specific reporting level should be clarified.

Step 3: Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) analysis aims to define the data that is required to assess the environmental and social impacts of the considered product. The recommended steps by the ILCD Handbook are adopted for inventory analysis for the E-LCA [23], while the S-LCA adopts the recommendations by Guidelines for Social Life Cycle Assessments of Products [14].

Environmental Life Cycle Assessment

Within the E-LCA, six steps need to be addressed in the Life Cycle Inventory Analysis.

1. Identifying processes for the LCI model
The first step aims to define what inventory data is required and forms the basis for the LCI model. This step draws upon the system diagram that was created and displayed in the scoping stage. This step should provide a thorough representation of the considered system, including all participating processes, any intermediate relationship between them, and links to the LCI database.

2. Data collection

Based on this identified LCI model, this second step describes which data is used per process step and how this data is collected.

3. Quality checking
Ensuring an adequate level of data quality and at the same time finishing the project within the allocated time frame should both be guaranteed. This third step checks the data quality by validating the completeness and accuracy of the used data.

4. Constructing LCI model and computing LCI results
After all unit processes have been identified and the required data is collected, the LCI model can be constructed. The corresponding calculations are based on reference flows, which can be defined as the flows that determine the amount needed of material for each unit process.

5. Preparing sensitivity analysis
Performing a sensitivity analysis is crucial for interpreting the LCA results since this analysis can show the extent of reliability and robustness of the conclusions. In addition, this analysis can also suggest where future research should concentrate to improve reliability. Therefore, this fifth step should describe the required data that needs to be collected as input for the sensitivity analysis.

6. Reporting
The reporting step comprises all necessary reporting of all findings during the LCI analysis. This concretely means that the following elements should be documented: (1) LCI model; (2) all unit processes; (3) metadata; (4) LCI results; (5) assumptions; and (6) data collection for sensitivity analysis.

Social Life Cycle Assessment

The Guidelines recommend eight consecutive steps for the life cycle inventory analysis [24]:.

1. Data collection for prioritizing
According to the Guidelines, businesses are responsible for addressing all social impacts in which it is involved. However, it may be too time-consuming to consider all entities within the supply chain so prioritizing is required to pinpoint areas where the risk of adverse social impact can be most significant.

2. Preparing for main data collection
After this prioritization is established, it is required to determine what information is needed to measure the social impacts and how this is done. This measurement can be realized by using indicators. Linking the indicators to the particular S-LCA impact categories is known as classification and should also be described in this step. A consensus on which indicators to use in the S-LCA lacks so it is crucial to give additional information for each indicators to improve objectivity in the interpretation of the results. Therefore, the following should be defined for every indicator: (1) indicator type; (2) data collection method; (3) data source; and (4) scale of data (international, national, sector, company).

3. Main data collection
This step encompasses detailed screening and monitoring of the supply chain to measure the indicators. To overcome subjectivity, triangulation of data in S-LCA is recommended by the Guidelines. This concept illustrates that the measured indicators should always be compared or contrasted with measured indicators by multiple sources.

4. Data collection for impact assessment
This step should collect data that is needed to aggregate the inventory data to impact categories.

5. Validation of data
To guarantee that data quality requirements are met, it is necessary to revise data validity during the data collection, as stated in ISO 14040.

6. Relating (main) data to the functional unit and unit process
The ISO standard emphasizes determining the relation between the gathered data and the Functional Unit (FU) and unit process. However, the Guidelines note that, because of the difficulty to link social impacts with a technical FU, the collected data may not necessarily be expressed as function of the FU.

7. Refining the system boundary
Refining the system boundary is recommended by the ISO 14040 standards, which suggests that it is required to verify whether a change in the system would change the outcomes of the assessment.

8. Data aggregation
Data aggregation can contribute to ensuring effective communication for stakeholders or decision-makers. However, the aggregation of LCI data should avoid that crucial data is lost which can consequently result in misleading interpretations.

Step 4: Life Cycle Impact Assessment

The Life Cycle Impact Assessment is the fourth stage of the LCA where the inventory data is translated into final environmental and social impact scores. Regarding the calculation of the environmental impact score, this step aims to determine how much each elementary flow (e.g., resource use of a product) contributes to an environmental impact. This conversion is needed since some of the gathered LCI are just quantities and lack in expressing impacts. Although this phase is mostly executed by software in the case of the E-LCA, it is still required to understand the underlying principles to decide on an appropriate impact assessment method and to successfully interpret the results. Regarding the computation of the social impact scores, the collected data needs to be translated in such a way that social impacts during the involved unit processes are identified.

In accordance with the recommendations of the ISO 14040 and 14044 standards, the following steps are incorporated into this research:

- Selecting of the LCIA method: refers to the selection of the considered impact categories (e.g., climate change, discrimination).
- Classification: this relates to classifying the LCI data to impact categories based on their known potential impacts. This process can involve difficulties since one dataset of the LCI can result in multiple impacts; however, the E-LCA software generally handles this difficulty. Important to note, such software has not been developed yet for the S-LCA, so the classification, in this case, is realized by incorporating the UNEP Guidelines [24]. Throughout this paper the term "Guidelines" is used to refer to the UNEP Guidelines for Social Life Cycle Assessments of Products. These Guidelines suggest which type of stakeholders can be affected by which impact categories.
- Characterization: refers to the translation of LCI into impact categories. In the case of the E-LCA, this is generally also done by the software and is typically realized by characterization factors (CF), which converts the relative each kilogram of material to an environmental impact. For example, by multiplying the weight of emissions (gathered in the LCI analysis) with its corresponding CF, the emissions or intervention contributing to the same impact

category can be summed. In the case of the S-LCA, the conversion of LCI data to impact categories is more challenging since not all collected data is quantitative. This might imply more subjectivity in the conversion process, meaning that detailed reporting about this process is required.

- Normalization: during normalization, the characterization results are put into perspective with a reference; for example, if the LCIA results are compared with the results from a similar study that assesses the same functionality (e.g., 1 kWh of solar energy vs. 1 kWh of wind energy). Since this step is optional by the ISO 14040/14044 standards, it is disregarded in this research.
- Weighting: this step prioritizes impact categories based on their relative importance. Since LCA is an analytical tool and lacks guiding decision-making, a value judgment of what is deemed superior or more significant is necessary. Also, this step is not recommended by the ISO standards and for this reason, excluded from the research.

Environmental LCA

In practice, the choice of the LCIA method also determines the classification and characterization practice. In recent years, many different LCIA methods have been developed and the most common methods published since 2000 are depicted in Figure 2.2. This figure shows the diversity of the LCIA method, demonstrating the importance of systematically identifying the most suitable one for a study. Note, this figure might be outdated since, for example, a more recent version (published in 2016) of ReCiPe is already developed but excluded in the figure. The LCIA method also determines the included impact categories. Generally, two types of impact categories can be recognized: (1) midpoint impact categories; and (2) endpoint impact categories. This distinction is frequently made and differs in the environmental cause effect chain.

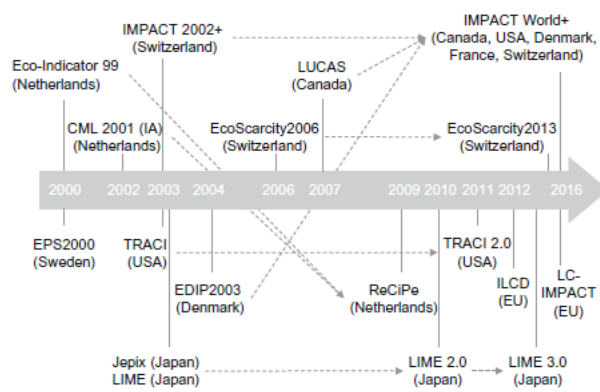


Figure 2.2: LCIA most common methods published since 2000 with country or region of origin (taken from Hauschild et al. (2017) [3]

Social LCA

In contrast with the E-LCA where the impacts are calculated by cause-effect modeling, the S-LCA applies a different processing strategy. Generally, two types of aggregation approaches can be recognized for an S-LCA. The first approach is based on a basic aggregation where the inventory data is aggregated by providing a single textual summary. The second, more complicated method employs reference points (for example, internationally set thresholds) to normalize inventory data and eventually aggregate this into a single value.

Step 5: Interpretation

The last phase of the LCA is the interpretation phase where results are evaluated and conclusions of the assessments were drawn. This phase both concludes relevant to the goal of the study and describes the robustness and weaknesses of the study. This latter can be validated by performing a sensitivity analysis, which determines how a dependent variable is affected by a different value of an independent variable under a specific set of assumptions.

2.2 Modeling approach

Although the steps within an LCA are clearly defined in the ISO standards, it is unrealistic to expect that LCA delivers a unique and objective result. This is mainly caused by the decisions that the LCA practitioner should take during the LCA procedure. Before starting with the LCA it is needed to decide on the LCA modeling framework, as recommended the ILCD Handbook [23]. This decision influences methodological decisions (e.g., input data). Since this selection can affect the outcomes of the study, systematic reasoning should be made on which approach is appropriate for the study. Within the LCA community, two main types of LCA approaches can be recognized among many publications: (1) attributional LCA (ALCA); and (2) consequential LCA (CLCA).

In recent years, the concepts of attributional LCA and consequential LCA have been widely defined by different authors. This research follows the definitions formulated by Finnveden et al. (2009), which is a widely used terminology [25].

- Attributional LCA: intends to describe the environmentally physical flows to and from a life cycle and its subsystems.
- Consequential LCA: intends to describe how environmentally relevant physical flows will change in response to possible decisions.

These definitions suggest that the attributional LCA aims to determine the attributed impacts, and the consequential LCA aims to identify the consequences of consuming a product [25]. Ekvall et al. (2016) recommend that using the attributional LCA is especially valuable when research intends to identify impacts, which can lead to the identification of hotspots within the supply chain or for labeling purposes of a product [25]. This attributional LCA only considers a small parts of a entire system and analyses this by isolating this from the rest of the world. It is assumed that the other part of the system (e.g., the economy) will not change. Contrarily, the consequential LCA aims to include the changes that might occur in the entire system. For example, if the consumption of product X will change the consumption of product Y is included. It is worth mentioning that the consequential LCA is capable of considering both positive and negative impacts. Figure 2.3 shows the illustration of the attributional and consequential LCA and indicates the corresponding research question.

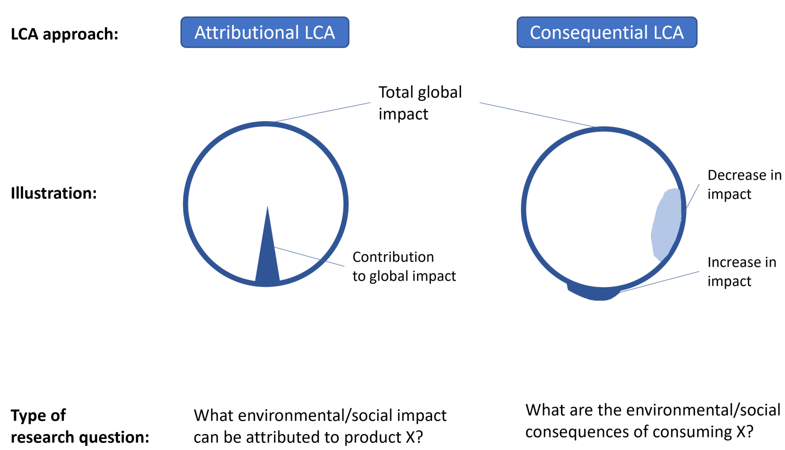


Figure 2.3: The meaning of the attributional and consequential LCA (based on Weidema 2003 [4])

2.3 Dealing with multifunctionality

Multifunctionality can be defined as a process that offers multiple services/products [24]. The LCA should establish a method to divide and distribute related environmental impacts across the multi-products when the product under investigation includes a multifunctional nature. This necessity has also been recognized by the ISO standards after which they have developed a hierarchy of solutions indicating which is preferred. There are essentially three strategies to deal with multifunctionality (listed based on preference): (1) sub-division of unit process; (2) the allocation method; and (3) the system expansion method. Important to note, the allocation method is commonly used for the ACLA where the environmental burdens of a process are divided across outputs. While the system expansion is frequently used for the CLCA to encompass the processes that are affected by the change in flows by expanding the system boundaries (without allocating) [3]. These methods for solving the multifunctionality are discussed in this chapter.

Subdivision of unit process

This method implies that the multifunctional problem can be solved by breaking down the multi-functional unit into smaller and separate processes. In other words, this strategy aims to separate the life cycle stages of the investigated product from the co-product. Figure 2.4 illustrates the nature of this method to solve the multifunctionality. This method of dealing with multifunctionality does not always succeed since multifunctionality is often characterized by a holistic nature, meaning that different phenomena are interchangeable with each other.

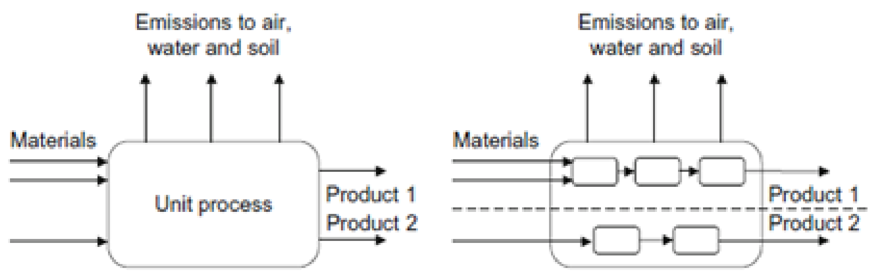


Figure 2.4: Solving functionality by subdivision (taken from Hauschild et al. (2017) [3]

Allocation method

The Attributional LCA intends to determine what share of the global environmental impacts belongs to the investigated product. In the context of the allocation problem, it is necessary to assess what portion of the multifunctional process's burdens belong to the product investigated. This allocation is based on a feature that the investigated product and the co-product have in common. This commonality can be, for example, mass, energy content, or price. Then, based on this commonality, the allocation factor allows for the quantification of the product's overall impact. In many ALCA the price feature is often used since this can consistently be applied throughout the life cycle [23]. However, a drawback is that the LCA results are affected by price varying over time.

System expansion method

The Consequential LCA strives to determine how the environmental impacts of the investigated product affect the global environmental impacts. The system expansion method is another strategy that can be applied to solve the multifunctionality problem. System expansion is the process of expanding the initial system to ensure equal functionality but, at the same time, allowing to assess the impacts. For example, to assess a combined heat and power plant, the system can be expanded by including a individual power plant in combination with a alternative that produces the heat. In this way, the functionality is kept intact but this allows for dealing with the multifuncionality process. This process is visualized in Figure 2.4.

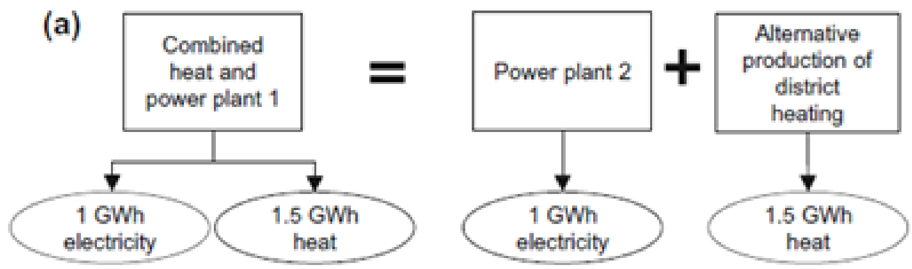


Figure 2.5: Solving multifunctionality by system expansion (taken from Hauschild et al. (2017) [3]

Chapter 3

Research Methodology

This section presents the chosen research methodology. Answering the research question leads to the analysis of social and environmental impacts of a typical PV module. For this purpose, it was decided to use both the environmental life cycle assessment (E-LCA) and the social life cycle assessment (S-LCA). The LCA methodology generally consists of four steps: (1) goal and scope definition; (2) collection of Life Cycle Inventory data; (3) performing the Life Cycle Impact Assessment; and (4) interpretation of the results from previous steps. This study separates the first step into *Goal definition* and *Scope definition*. This research incorporates the ILCD guidelines defined by the European commission [23]. The objective of this chapter is to describe how these phases are applied in this research.

3.1 Goal of the study

Intended applications of the results

The primary objective of this study is to identify the environmental and social impacts of a typical PV module. This identification can then conclude on where in the supply chain the social and environmental impacts are most significant (= hotspots). These identifications allow to address these areas which should be prioritized for action.

This objective leads to the following intended applications for the LCA community:

1. Demonstration of updated environmental impacts and the first identification of social impacts of a PV module from a life cycle perspective.

2. Identification of environmental and social hotspots within the life cycle of a PV module.

3. Support the development of the S-LCA methodology by additional testing and suggesting possible refinements, resulting in a more robust methodology.

Furthermore, the intended applications for Ecorus are also listed:

1. Demonstration of severe social and environmental hotspots in the supply chain of Ecorus. This demonstration allows Ecorus to address these problem areas, which can lead to measures that improve the social conditions for the involved stakeholders and lower environmental impacts throughout the life cycle. These hotspots stand out since they face the greatest risk of adverse effects on the operations or value chain of Ecorus, hence these hotspots should be prioritized.

2. Documentation of the environmental and social performance of one of the key products of Ecorus. The S-LCA and E-LCA results can be used for the sustainability report that Ecorus are committed to write on anual basis.

Limitations due to methodological choices

Since the S-LCA is still a new methodology, this social assessment serves as a starting point for further engagement and learning. This might result in a relatively low level of detail and denotes the importance of carefully interpreting the outcomes of this S-LCA. In addition, the representativeness of the identified social impacts may be low, because many uncertainties are involved regarding the supply chain identification and data quality. Although numerous efforts, transparency of the supply chain is still limited and results in many uncertainties regarding tracing the involved materials and suppliers. Due to limited resources for this research, the supply chain will be described concisely, which could result to lower representativeness of the social impacts compared to the actual impacts. Regarding the E-LCA, the biggest constraint relates to the gathered inventory data. Although measuring actual processes might theoretically guarantee the highest data quality, this study uses an LCI database that contains data for the involved processes. This is primarily due to limited resources and accessibility of these processes. The Ecoinvent inventory database, which is considered the most complete database in the LCA community, is used in this research. However, some processes still use outdated and generic data, hence uncertainties may result from this.

Decision context and reasons for carrying out the study

Although Ecorus strives to be socially concerned, the actual environmental and social impacts of its operations, its supply chain, or even through the end consumers are as yet unknown. That is why Ecorus seeks to proactively explore these impacts related to the upcoming large-scale PV capacity. These identifications allow Ecorus to address these impacts and can by doing so contribute to making societies more sustainable. Furthermore, the study aims to support a decision, but regardless of the decision made it is expected that this won't result in structural changes to either the investigated system or in interacted systems. Since this study intends to identify social and environmental hotspots, it is assumed that this study can be classified into micro-level support. The system may undergo some minor changes as a result of the E-LCA and S-LCA, but it is assumed that these changes won't lead to structural changes.

Target audience

The target audience for this research is bipartite. The first group is Ecorus, which is the commissioner of this research. Second, this research aims to provide the first assessment of social impacts and to update the environmental impact of the PV module. Therefore, the LCA community is considered to be the second group. Overall, it is intended to clearly communicate all findings so that this study is understandable for both target groups.

Comparative studies to be disclosed to the public

Both the S-LCA and E-LCA can be used for comparative purposes; for example, to conclude on the impact of technological advancements on environmental impacts, or to examine the social impacts of various renewable technologies. It is intended to report methodological choices transparantly to allow that this study can be compared under same conditions. Care should be taken, nonetheless, as discrepancies in methodological choices can disturb a fair comparison and can lead to misleading interpretations.

Commissioner of the study and other influential actors

As mentioned earlier, Ecorus is the research commissioner of this project. The degree of influence on the study by Ecorus was limited to the alignment of the goal and scope definition. The main influential factor in this study was related to the sourcing of the inventory data for the S-LCA. Since economic interests can be involved with the outcomes of the S-LCA, the data that was provided by the suppliers of Ecorus may be subjective to hide possible social impacts. Hence, the reliability of the provided data can suffer.

3.2 Scope of the study

Deliverables

The main deliverable for both the E-LCA and S-LCA are the LCIA results. Formulating the LCI results transparently allows for reproducing the LCA studies, while the LCIA results are documented for all impact categories by numerical values. In the end, conclusions about the social and environmental hotspots within solar PV supply chain were drawn.

Object of the assessment

Since the research question employs the concept of a “typical” PV module, it is important to clarify this concept. The object for this research is a single-crystalline silicon (sc-Si) PV module because this type of PV cells have the largest market share. Evidently from a 65% global market share in 2019 and a forecasted share of 80% by 2030 [26]. Additionally, PV modules can also be classified into two types of power generation: (1) single-side (monofacial); and (2) double-side power generation (bifacial). The monofacial module is considered in this study since it is currently the most utilized module at Ecorus.

An sc-PV module typically consists of five components:

1. Frame – for protecting the module and to provide the structure to mount the panel
2. Glass – for protecting the cells from the weather
3. EVA (Ethylene-vinyl acetate) – for preventing humidity and dirt from penetrating the solar panel
4. Cells – for converting the sunlight into direct current
5. Backsheet – for providing mechanical protection and electrical insulation

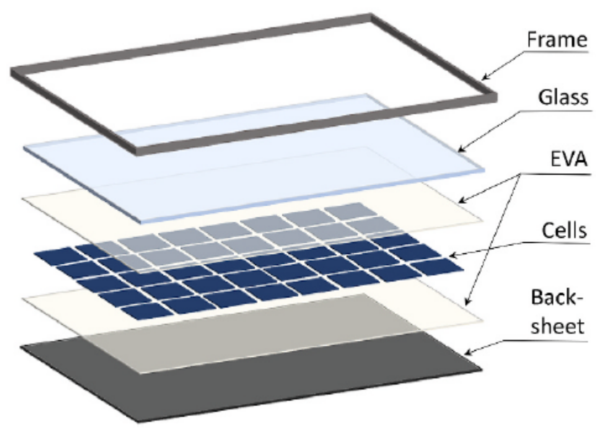


Figure 3.1: Structure of sc-Si PV module (taken from Fraunhofer ISE (2022)) [5]

Another crucial component within the object definition is the Functional Unit (FU), which can be defined as the studied subject of the LCA. In this E-LCA, the FU is defined as 1 m_2 of the sc-Si PV module, excluding the balance of the system (BOS). The BOS includes all components of a PV system other than the solar panels, such as cables, switches, mounting systems, and inverters. The BOS is excluded because the PV module is the main focus of this research. On the contrary, this research does not express the social impacts per functional unit. This is because this type of assessment typically uses semi-quantitative, which makes it challenging to directly link social phenomena to a technical specificized FU [24].

LCI modeling framework and handling of multifunctional processes

A thoughtful decision is required since the selected LCA method can affect the LCA outcomes. The choice of the LCA method will be based so that the type of information that this method can initiate and matches the intended results of the research. The goal of the study, identifying impacts, implies that the attributional LCA is suited for this research. Furthermore, the ISO standards recommend the subdivision method for dealing with multifunctionality if it is possible to separate the production of the PV module from the production of the co-product. This research assumes that there are no co-products involved, thus this study neglects the multifunctionality nature.

System boundaries and completeness requirements

As can be observed in Figure 3.2, this study adopts a cradle-to-grave assessment, meaning that the extraction of raw material, material-, product manufacturing, transport, installation, and end of life are included (more detailed explanation of the production steps is provided in Chapter 4). Furthermore, because the PV module is the major emphasis, the BOS components are disregarded. It is assumed that the PV module does not have any environmental impact during the use phase; however, there can be an impact if the module's maintenance would be included.

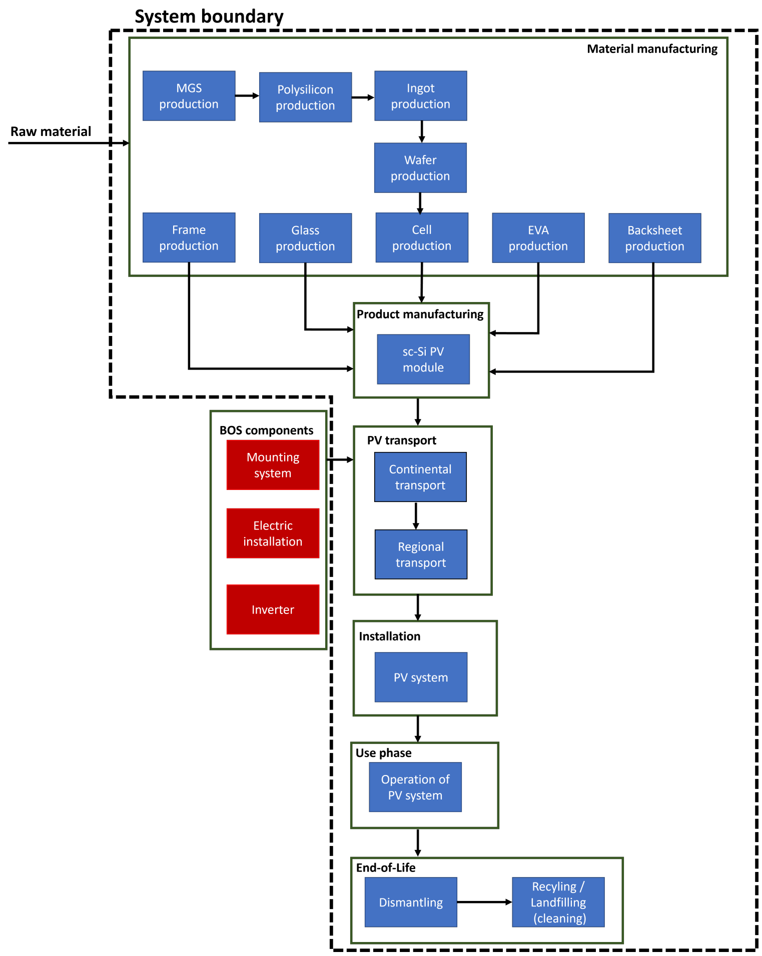


Figure 3.2: System boundaries

Representativeness of LCI data

The quality of the inventory data heavily determines the quality of the research, hence evaluating the inventory quality is an essential stage in LCAs. This is especially important in this study since the data collection may be one of the most challenging aspects of this research. The Representativeness intends to identify instances where data sources lack in meeting the necessary standards and to undertake measures to increase the data quality. Many challenges are related to acquiring high-quality data, such as geographical restriction, political restrictions, and budgetary restrictions. Bonilla and Fu (2022) proposed a data quality matrix assessment method that aims to assess the data quality for S-LCAs and is also incorporated in this research [11]. This method is constructed based on the Pedigree matrix [4] and the data quality assessment described in the 2018 Handbook for the Social Impact Assessment of Products [24]. Table 3.1 shows this data quality validation checklist. This table shows the data quality requirements (indicated in the columns) and the criteria for determining the data quality score (indicated in the rows). The ratings run from 1 (best) to 5 (worst) and should ideally be assigned to all indicators. The evaluation is based on four criteria: (1) accuracy, integrity, and validity; (2) timeliness or temporal correlation; (3) geographical correlation; and (4) technological correction. The first evaluation criterium considers the source of data and the data collection method, *timeliness* compares the time of the study with the time of data collection, *geographical correlation* compares the location under study and the collected data, and the latter criteria refers to the reflection of the extent to which the technologies are correlated. Bonilla and Fu (2022) state that the average score of every indicator should be less than 3 to pass the data quality assessment [11]. After the life cycle inventories are provided in Chapter 3.3.2, these were evaluated based on the above mentioned categories.

Although no scores were assigned for used inventory for the E-LCA (since this method was particularly developed for S-LCAs), the inventory was evaluated in terms of these categories.

Table 3.1: Data quality assessment criteria [11]

Criteria	**Accuracy, integrity, and validity**		**Timelines**	**Geographical correlation**	**Technological correlation**
Score	**Primary data**	**Secondary data**			
1	Verified data based on measurements	Reports from more than one well-established independent organization	Data from current reporting period (or <1 year old)	Data from specific site under study	Data from enterprises and processess under study
2	Non/verified data with documentation or verified data partially based in assumptions	Report from a well-established report organization	Data from previous reporting period (between 1 and <2 years old)	Data from other sites of the company in the same region	Data from processes under study but from different enterprises
3	Non-verified data based on assumptions or grey data	Independent but similar claims made by various sources	Data is 2 years old	Data from relevant sites of the company in other regions	Data from processes under study but from different technology
4	Qualified estimate (e.g., by expert) or non-scientific report	Unverifiable claims found on internet and social media	Data is 3 years old	Data from other companies in the same region with similar production conditions	Data on related processes but from same technology
5	Non-qualified estimate or unknown source	Non-qualified estimate or unknwon source	Data is more than 3 years old. Data should be 15 years old	Average sector or country data from public or third-party database provider	Data on related processes but from different technology

Preparation of the basis for the impact assessment

This phase describes the used impact categories that will be used for the LCIA. The choice for the LCIA method can be based on a pragmatic point of view. Namely, the software can also significantly reduce the range of available LCIA methods. This research uses Activity Browser and is based on the following reasonings: (1) this GUI is freely accessible - given that the budget for this research is limited, an open and free software package was necessary; (2) this GUI offers advanced tools for data analysis and LCA modeling, which is beneficial for state-of-the-art LCA research [27].); (3) it is a relatively accessible software so limited programming skills are required; and (4) it is compatible with the Ecoinvent database.

Selecting the PEF impact categories were not feasible due to software constraints, suggesting that other impact categories were required. Along with certain other impact categories, the activity browser instantly installs the ReCiPe impact categories, making them available for usage right away. Also, the ReCiPe method is beneficial for this study because it is updated regularly to incorporate new data and new research. Therfore, the impact categories that are considered are based on the ReCiPe midpoint 1.13 categories and are used in this research for the E-LCA.

The S-LCA aims to identify social impacts that may affect involved stakeholders along the life cycle of a solar panel. For this purpose, the *Guidelines for Social Life Cycle Assessment of Products* developed by the UNEP/SETAC Life Cycle Initiative is adopted [14]. Generally, social impact can occur in five types of stakeholder categories: workers (during all production steps), local community, society, children, and consumers. Then these stakeholders will be evaluated in terms of the suggested impact categories and indicators suggested by the *Methodological Sheets for Subcategories in S-LCA 2021* [28].

Special requirement for system comparisons

The ILCD guideline requires that uncertainties should be addressed and communicated to prevent misleading LCA results and the misuse of LCA in comparison statements. This requirement was incorporated in this research and is discussed in Chapter 7.

Needs for critical review

This study includes a critical review and this was done in an interactive process during all involved steps of the LCA. For example, the goal and scope definition was carefully defined and reformulated with Ecorus, while the collection of the inventory data and the execution of the impact assessment was realized in close collaboration with the supervisors from the university.

Planning the reporting of results

This study communicates the results both internally to Ecorus and will also be publicly released by the Technical University, Eindhoven.

3.3 Life Cycle Inventory Analysis

3.3.1 Environmental LCA

The Life Cycle Inventory (LCI) for the E-LCA aims to define the data that is used that is needed to assess the environmental impacts of the considered product. Table 3.2 shows the used LCI for the E-LCA. The most accurate inventory dataset can be realized by directly retrieving data from Ecorus, its suppliers, or other partners. Although this type of data is preferred, LCI databases are used for the environmental LCI due to limited resources and a lack of supply chain transparency. The used inventory for the material and product manufacturing matches with the available processes in Ecoinvent, which makes it simple to apply the inventory in the E-LCA. Frischknecht et al. (2020) provide the inventory for the Europese, American, Chinese, and Asian production processes [2].

Table 3.2: Life Cycle Inventory for the E-LCA

Stage	Used inventory
MGS, polysilicon, ingot, wafer, cell, module production	This inventory is based on the most recent consensus LCI among PV E-LCA experts and presented by Frischknecht et al. (2020). This LCI comprises precisely calculated in-puts and outputs for all sc-Si manufacturing processes. To represent the MGS production table 6 was used, the polysilicon production uses table 7 and 8, ingot production employs table 9, wafer production uses table 12, cell production table 16, and module production (EVA, backsheet, glass, and aluminium are included) table 19. Because of the comprehensiveness and recentness of this LCI, it was chosen to employ this inventory for this study. In addition, Ecoinvent, a worldwide environmental database is used for gathering background data and for estimating industry process emissions. Due to its extensive database of over 18,000 processes from numerous industries, Ecoinvent is a frequently used database for life cycle analyses.
Transport	The transportation from China to the Netherlands of the PV module is based on intercontinental freight ships from the harbor of Shanghai to Rotterdam. Additionally, the PV modules are distributed by trucks to the project locations. This data is obtained through own modelling and is explained in more detail later in this chapter.
Installation	The installation phase is based on data from a typical PV plant installed by Ecorus. This phase is incorporated by including all machinery involved (power generator, forklift, excavator, etc.). Also this data is obtained through own modelling and the made assumption are discussed later in this chapter.
End-of-Life	The End of Life (EoL) treatment is modeled based on Frischknecht et al. (2017) and assumes the recycling of glass, frame, and cabling, while silicon components and polymers are landfilled or burned. Obtained from Frischknecht et al. (2017). Table 3.1 and 3.2 were used as inventory data to represent the End-of-Life stage.

Assumptions

The assumptions made for the E-LCA are listed below. Note, the assumptions for the energy mixes are discussed in Chapter 4.

Transport assumptions

The transportation is assumed from China to the Netherlands, since Ecorus is importing entirely from Chinese PV module suppliers. The required transport is based on intercontinental freight ships from the harbor of Shanghai to Rotterdam (19,994 km) [2]. Consequently, the PV modules are distributed by trucks from the harbor of Rotterdam to the project location (150 km), and its location is based on an already executed project by Ecorus.

Installation assumptions

The construction of a solar plant involves numerous diesel-based machines, all of which have an impact on the environment. For a ground solar project, the following types of machinery are frequently used: (1) forklift truck – for transporting materials; (2) ramming machine – for direct ramming of steel cross-section into the ground (to attach the panels); (3) excavator – for digging that allows for cable management; and (4) generator – for supplying the site (equipment) with its necessary energy. The effective usage per machine type was estimated based on an interview with a site manager of Ecorus (responsible for the coordination and execution of the installation of a solar plant). The total operating hours for the entire project for the forklift truck, ramming machine, excavator, and generator were estimated at 4080, 800, 800, and 800 hours, respectively. By dividing the total working hours by the total surface area of the solar plant (32697 of PV modules multiplied with 2.58 m_2/panel), these total operating hours were converted into operating hours per square meter of PV module. During these operation hours, greenhouse gas emissions can be emitted leading to environmental impacts.

EoL assumptions

Generally, two approaches can be adopted for obtaining the life cycle inventory for EoL: (1) the cut-off approach; and (2) the end-of-life approach. This latter allows for the calculation of the net environmental benefit, while the cut-off approach complements the life cycle inventory data [29]. This research chose the cut-off approach since this is in line with the goal of the study. This results in the following allocation factors (added together = 1): 0.5 for the treatment, 0.024 for the glass cullets, 0.154 for the aluminium scrap, and 0.322 for the copper scrap.

Representativeness of LCI data

The used inventory are evaluated in light of the data quality assessment criteria mentioned in Table 3.1.

- Frischknecht et al. (2020): Although the this LCI is based on a PV module of 195 W_p per square meter which is slightly lower than the currently utilized PV module, it is expected that the technological and geographical correlation is appropriate since the most recent Chinese-specific inventory is used. Also the most recent energy mix is updated implying that the involved technologies are also accurately represented. In terms of timelines, it is expected that this is also satisfied since the majority of the LCI processes are updated in 2020.
- Ecoinvent v3.8: this database is updated in 2021 which results in an appropriate level of timelines. Furthermore, almost all Chinese site-specific processes were included by selecting Chinese processes from the Ecoinvent database, implying that the geographical and technological correlation is satisfied. Furthermore, the energy mix that has a huge influence of the results is updated with the most recent characteristics.
- Transport and installation: this inventory was obtained by interviewing a site-manager from Ecorus and this phase was represented with processes from Ecoinvent. In terms of technological representativeness, this might be unsatisfied since the actual machinery/transport don't exactly match with the selected processes from Ecoinvent (e.g., mismatch between mechanical power)
- Frischknecht et al. (2017): this inventory is slightly outdated since this database was provided in 2017. This might lead to an inaccurate level of technological representativenss and timelines. Furthermore, it is assumed that the geographical correlation is appropriate since the used European inventory matches with the expected location of EoL.

3.3.2 Social LCA

Prioritization

Prioritization is the first and necessary step when conducting an S-LCA. This is done since it is expensive, time-consuming, and frequently irrelevant to gather data for all involved organizations in the production, transport, use, and EoL of a product or service [14]. This prioritization starts with identifying the value chain, which specifies the involved businesses, their locations, and the stakeholders involved and is discussed in Chapter 4. This prioritization process can be realized by using the Social Hotspot DataBase (SHDB), which aggregates social risks (when considering over 100 social indicators) related to a product over the entire life, allowing to conclude on the most severe social impacts. Although using the SHDB seems to be a promising method for prioritizing, it won't be implemented in this research due to budgetary considerations.

The considered life cycle stages within the supply chain can be associated with different geographical locations because of the global economy, meaning that a wide variety of stakeholders can be involved in an S-LCA. Freeman R. (1984) defined stakeholders as: “Those groups and individuals that can affect, or are affected by, the accomplishment of organizational purpose” [30]. Multiple organisations can be identified when defining the supply chain of a PV module. When referring to stakeholders, this can generally be divided into five categories: (1) workers/employees; (2) local community; (3) society (national and global); (4) consumers (end-consumers and consumers that are part of each step of the supply chain; (5) children; and (6) value chain actors [24].

In conclusion, the following decisions were made for prioritizing purposes:

- This research prioritizes by emphasizing the worker stakeholder group and putting less focus on the other stakeholder groups. This resulted in more indicators for this prioritized group. It is expected that the worker stakeholder group can be linked most directly with a product compared to the other stakeholder groups, suggesting that workers are more likely to be exposed to social impacts. This means that the following workers are considered: (1) the Chinese workers for the MGS and polysilicon production; (2) Chinese workers for the ingot, wafer, cell, and module production; and (3) workers for installing the PV modules in the Netherlands. More details about the geographical locations is discussed in Chapter 4
- It was chosen to put the mhe main focus on the MGS, polysilicon, ingot, wafer, cell and module manufacturing. This means that other required production steps (e.g. frame and glass production), but also transport, maintenance, and End of Life are neglected. This decision was made to constrict the project scope.
- Only the Chinese local community, society, and children are included, meaning that the Dutch local community, society, and children are excluded for the S-LCA.
- Only Dutch consumers are considered.

Data collection

This stage of the S-LCA might be the most challenging since it is expected that obtaining reliable data to represent the Chinese workers is complex since obtaining site-specific data is unfeasible for the time being. Currently it is practically impossible to enter the Xinjiang region since this province seems to be a police state and the presence of still valid strict corona restrictions (based on interview with Dutch embassy). Table 3.3 shows the used LCI for each stakeholder group. The indicators are measured with the following sources:

Table 3.3: Life Cycle Inventory for the S-LCA

Stakeholder group	**#**	**Inventory**
Workers - MGS and polysilicon production	1	*"In Broad Daylight: Uyghur Forced Labour and Global Solar Supply Chains"* from the Sheffield Hallam University [31]
	2	*OHCHR Assessment of human rights concerns in the Xinjiang Uyghur Autonomous Region, People's Republic of China* from the United Nations Human Rights [32]
	3	Solar supply chain expert: interviews were conducted with a knowledgeable expert onsolar supply chain, with decades of experience working with megallurgical grade silicon (MGS) suppliers in China. He's been keeping up to date on international supply chains in the solarsector and has visited around 100 Chinese MGS producers since 1999 [Chapter].
	4	First secretary at Dutch embassy in Beijing at the Ministry of Foreign Affairs: interviews were conducted with expert on human rights in China [Chapter]
	5	HollandSolar: the Dutch solar industry association since 1983.
Workers - Ingots, wafers, cells, and modules production	6	This worker group was represented by sending a questionnaire to JA Solar. This supplier manufacturers all these productions.
	7	Sustainability report from JA Solar [33]
Workers - Installation	8	The required data to represent the involved workers during the installation was obtained by directly interviewing employees from the installation parties. In total, several workers were interviewed that work for different installation companies. Refer to Chapter for an example of the interview.
Chinese local community, society, and children	9	Desktop research was applied to represent these stakeholder groups. Search terms related to the indicator names were applied to find data.
Dutch consumers	10	Ecorus has concluded the majority of Power Purchase Agreements PPA) in recent years together with Greenchoice. Therefore, the end-consumers of Greenchoice are considered to represent this stakeholder group. To represent this group, the sustainability report and desktop research was used. [34].

Representativeness of LCI data

The used inventory to represent the stakeholder groups are evaluated based on their level of representativeness and the results are presented in Table 3.4. According to Bonilla and Fu (2022), the average score of inventory should be less than three to pass the data quality assessment. The table revealed that the Chinese local community, Chinese society, and Chinese children stakeholder groups don't meet this requirement. The most effective measure would be to obtain site-specific inventory data to reflect these stakeholder groups. This table also suggests that the inventory used to represent the worker for ingot, wafer, cell, and module production and the Dutch customers meet the requirements. However, it is expected that despite meeting the requirement (score ¡ 3), the inventory is incapable of properly representing this worker group. This is because the score is calculated using arithmetic averaging, meaning that any bad value of one category can be compensated by a good value of another category. To address this shortcoming, it might be worthwhile to implement a scoring system that disqualifies a score if any of the categories is exceedingly high.

Table 3.4: Representativeness of S-LCA inventory

		Data quality criteria				
#	**Inventory**	**Accurary, integrity, and validity**	**Timeliness**	**Geographical correlation**	**Technological correlation**	**Score**
1	Sheffiel Hallam University	2	2	2	2	2
2	UNNHR	2	1	2	2	2
3	Solar supply chain expert	3	2	4	2	2.75
4	Dutch embassy	3	2	2	2	2.75
5	Hollandsolar	3	2	2	2	2.75
6	Questionnaire	5	1	1	1	2
7	Sustainability report JA Solar	5	1	1	1	2
8	Interviews with installation workers	2	1	1	1	1.5
9	Desktop research to represent Chinese society, Chinese local community, and Chinese children	4	4	5	4	4.25
10	Sustainability report Greenchoice	5	1	1	1	2

Indicator selection

To measure the impact categories, indicators are used. The selection of indicators can be complex since a universal set of indicators lacks due to the wide range of S-LCA applications. The stakeholder groups are evaluated in terms of the suggested impact categories and indicators suggested by the *Methodological Sheets for Subcategories in S-LCA 2021* and adopted based on their relevance for the study [28]. Refer to Chapter for the indicator selection for each stakeholder group. It is essential that additional information is provided per indicator to guarantee transparency and objectivity. As recommended by Bonilla-Alicea and Fu (2022), the following characteristics of every indicator should be mentioned, followed by the implementation for this research [11]:

1. Indicator type - since the goal of the S-LCA is to identify severe social hotspots rather than identifying the magnitude of the impact, only semi-quantitative (yes/no) indicators are incorporated that indicate whether the impact is positive or negative.

2. Related impact category - reflects topics of importance of stakeholders; for example, working conditions, health and safety, corruption, fair salary. Refer to Chapter 3.4.2 for an overview of all impact categories.

3. Related stakeholder group - it should be clear which stakeholder is represented by the indicators. This is presented in Chapter .

4. Desired direction - the desired direction is used as a reference to determine whether the social impact is positive or negative and is also presented in Chapter

5. Data source - the data source for allocating a certain value to the indicator should be explicitly reported and is mentioned for every indicator.

6. Scale of the indicator - the indicator can be expressed in several scales; for example, region, sector, or company.

3.4 Life Cycle Impact Assessment

3.4.1 Environmental LCA

The impact categories that are considered are based on the ReCiPe midpoint 1.13 categories and are used in this research for the E-LCA and are shown in Table 3.6 with their units and explanation. The main goal of the ReCiPe method is to translate the extensive list of life cycle inventory into a small number of indicator scores [35]. These indicators' scores can be influenced by the predefined cultural perspective. These perspectives reflect a range of options on topics such as timing or assumptions on future technology development. Generally, three different perspectives are recognized within the ReCiPe impact assessment method:

1. Individualist: optimistic view over the near future, believing that technology may prevent many issues.
2. Hierarchist: this is a consensus view and is sometimes regarded as the default model because it is frequently found in scientific research.
3. Egalitarian: based on long-term and precautionary principles.

It was chosen to calculate the environmental indicators scores with the hierarchist perspective. This perspective was opted since this is a middle ground between the two extreme perspectives and this is also the default perspective in scientific research.

In order to conclude on the impact of updating the E-LCA, both the results were presented for a so-called "base case" and the "updated E-LCA. The base case represents the E-LCA with the Frischknecht et al. (2020) inventory, while the updated E-LCA also incorporates this inventory but it also updates the energy mix and adds the transport and installation stages.

After the life cycle impact assessment results are presented, two sensitivity analyses were executed to determine how the results behave when changing a parameter under a given set of assumptions [36]. Two different sensitivity analyses are executed: (1) one that analyses the results of a changing Chinese electricity mix; and (2) one that examines the influence of different ReCiPe perspectives. Refer to Table 4.2 for the used electricity mixes for the 2035 and 2050 outlooks.

Table 3.5: Chinese electricity outlook for 2035 and 2050 (based on Figure 7.2 [8])

Source	**Share 2035**	**Share 2050**
Coal	0.100295	0.05
Natural gas	0.040123	0.013273
Hydro	0.121732	0.119486
Oil	0.100295	0.013273
Wind	0.387187	0.496737
Solar	0.178621	0.230031
Nuclear	0.055162	0.05971
Biofuel	0.016586	0.017489

Table 3.6: Selected impact categories for the E-LCA

Impact category	**Unit**	**Explanation**
Agritcultural land occupation	m^2 /year	The surface of agricultural land that is occupied per year
Climate change	kg CO_2-Eq.	Long-term changes in temperature and weather patterns.
Fossil depletion	kg oil-Eq.	Depletion is defined as the process in which a resource's rate of consumption exceeds its rate of replenishment. The amount of extracted fossil fuels
Freshwater ecotoxicity	kg 1.4-DCB-Eq.	The chemical emissions that can be emitted into waters
Freshwater eutrophication	kg P-Eq.	The possible rise of nutrient levels in waters.
Human toxicity	kg 1.4-DCB-Eq.	The potential harm of released chemicals into the environment
Ionizing radiation	kg U235-Eq.	Ionizing radiation is made up of subatomic particles or electromagnetic waves with enough energy to ionize (when molecules or an atom acquire a negative or positive charge by gaining/losing electrons) atoms or molecules.
Marine ecotoxicity	kg 1.4-DCB-Eq.	The effect that toxic compounds have on marine ecosystems and can result from air pollutants.
Marine eutrophication	kg N-Eq.	The response of a marine ecosystem to an overabundance of a nutrient is known as marine eutrophication. For instance, this nutrient could be nitrogen (N). The overgrowth of aquatic plants and algae caused by this overstimulation of nutrients can ultimately block light to deeper waters which can harm biodiversity.
Metal depletion	kg Fe-Eq.	Depletion is defined as the process in which a resource's rate of consumption exceeds its rate of replenishment. Although this impact category contains many different types of metals, it is represented by the equivalent amount of iron.
Natural land transformation	m^2	The area of land that is transformed and occupied for a certain time
Ozone depletion	kg CFC-11-Eq.	The particles that have an impact on the ozone layer. Ozone depletion leads to lower ozone levels, which increases UV radiation exposure at the Earth's surface and lessens the protection from the sun's rays.
Particulate matter formation	kg PM10-Eq.	A lot of particulate matter (e..g, sulfur dioxide, and nitrogen oxides) are emitted from power plants and in industries and can be harmful if they are inhaled. PM10 = Particulate Matter, with a size of up to 10 micrometers).
Photochemical xidant formation	kg NMVOC-Eq.	The photochemical oxidants particles which is product that is created when a nitrogen oxide and volatile organic compound react. This can ultimately also results in photochemical smog and can also harm health of people.
Terrestrial acidification	kg SO_2-Eq.	The changes in chemical properties of the soil into acidifying forms. As a result of an increase in acidifying nutrient concentration in the soil, this can lead to a lower photosynthetic rate and decreased plant diversity numbers.
Terrestrial ecotoxicity	kg 1.4-DCB-Eq.	The environmental pollutants and their environmental impact on land ecosystems.
Urban land occupation	m^2/year	Urban land occupation calculates the square meter of urban land that is occupied for a specific period.
Water depletion	m^3 water-Eq.	Water depletionmeans a reduction in the total amount of usable water due to human activities and changes in the environment.

3.4.2 Social LCA

In contrast with the E-LCA where the impacts are calculated by cause-effect modeling, the S-LCA applies a different processing strategy. As discussed earlier, generally, two types of aggregation approaches can be recognized for an S-LCA. The first approach is based on a basic aggregation where the inventory data is aggregated into a single textual summary. The second method aggregates the information into a numerical value. This S-LCA starts with assigning a numerical value to all indicators (0 or 1). In case a "0" is assigned, it denotes a potential social risk of impact, whereas a "1" shows that the indicator value corresponds with the desired value. This assigning process will be supported by a indicator narrative. Then all indicator values for each stakeholder group are aggregated by arithmetic averaging. Refer to Table 3.7 for the considered impact categories for the S-LCA.

Table 3.7: Selected impact categories for the S-LCA

Worker	**Local community**	**Consumer**	**Society**	**Children**
Freedom of association and collective bargaining	Access to material resources	Health and safety	Public commitments to sustainability issues	Education provided in the local community
Child labor	Delocalization and migration	Feedback mechanism	Contribution to economic development	Health issues for children as consumers
Fair salary	Cultural heritage	Consumer privacy	Prevention and mitigation of armed conflicts	
Working hours	Safe and healthy living conditions	Transparency	Technology development	
Forced labor	Respect of indigenous rights		Corruption	Children concerns regarding marketing practices
Discrimination Health and safety Social benefits Employment relationships Sexual harassment	Secure living conditions	End-of-Life responsibility	Poverty alleviation	

3.5 Interpretation

This subsection seeks to find the LCA's hotspots and the greatest contributors to the social and environmental impacts. Regarding the S-LCA, the results will be analyzed by verifying which stakeholder group has the lowest aggregated value (ranging from 0 to 1). Here a value of "1" means a low risk on social impacts, while a "0" represents that there is a high chance of social impacts. This allows to identify the stakeholder groups that are most affected by the by a solar panel. Regarding the environmental hotspot identification, this was done by looking at which processes came back most often in the impact categories.

Chapter 4

Solar Photovoltaics Supply Chain

In order to identify the associated social and environmental impacts of a solar panel, the supply chain of a PV panel should first be identified. This chapter aims to establish this identification. The importance of tracing the solar supply chain was recognized by the Solar Energy Industries Association (SEIA). This organization launched a traceability protocol and these recommendations are incorporated in this research [6]. For example, the SEIA claims that the supply chain identification should identify the involved steps and each step should contain details about the product being produced, the manufacturing process, the name of the producer, and the location of the production. Although this description can take many different shapes, the fundamental components are shown in Figure 4.1.

Figure 4.1: Three-step supply chain map (taken from SEIA (2021) [6])

When translating this figure into the context of the PV module manufacturing, the following production stages can be recognized (shown in Figure 4.2): metallurgical grade silicon (MGS), polysilicon, ingot, wafer, cell, and module assembly. Note, as discussed in Chapter 3.2, the BOS components, aluminium frame, EVA, and backsheet production are excluded for the S-LCA and are therefore also disregarded for the supply chain mapping. However, these disregarded processes are included for the E-LCA and this inventory data is provided by Frischknecht et al. (2020) [2].For each stage in the supply chain, it is intended to conclude on the manufacturing process, the involved producer, the location of the production, and the electricity mix present during the process. The applied energy mix in the E-LCA heavily influences the outcomes of the analysis, implying that careful consideration is required. Since Eoinvent v3.8 contains data for different technology shares in the electricity mix that is based on 2014, it is crucial to update these shares with the most recent proportions.

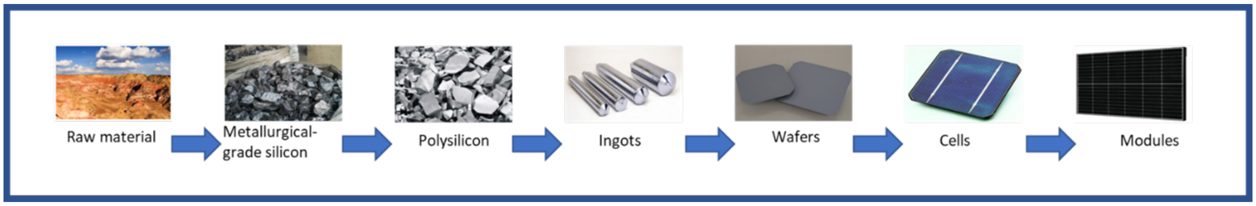


Figure 4.2: High-level supply chain of a typical PV module

China contributes considerably in supplying the global PV-components. Factors including low labor costs, centralized supply chains, and significant efforts by Chinese authorities has resulted in the fact that currently China is the world leader in the solar industry. This huge market share is illustrated in Figure 4.3. This figure shows that the worldwide PV supply chain is mostly dependent on ingot and wafers from China while cells, modules and polysilicon can be obtained from sources outside of China. Currently all imported PV modules of Ecorus are provided by JA Solar, one of the biggest PV manufacturers in terms of PV module capacity and is also for this research considered as the PV module manufacturer.

High-purity level of quartz

The supply chain of the sc-Si PV module starts with extracting high-grade quartz, which can be found in vast deserts. The silicon incorporated in sc-Si PV modules originates from silica, which is the second-most prevalent mineral in the Earth's crust. However, there is a need for extremely high purity of silica, implying that there are restriction on the types of quartz that can be used. There are primarily two method used to mine quartz for silica: (1) quartz can be found often in riverbeds from broken mountain ranges; or (2) quartz can also be exploited underground, which can cause social impacts since released dust particle can be fatal if they are inhaled [7]. These methods can impact ecosystems since these typically result in a large scar where the quartz is mined. Through web searches and interviews with the solar supply chain expert, an attempt was made to locate the extracting of quartz and involved companies. The conclusion is that there is a lot of uncertainty and unknown about the location of these processes due to a lack in transparency. However, considering that quartz is generally an inexpensive material, it is reasonable that the transport costs should remain low. Therefore, it is expected that the quartz extraction takes place close to where the MGS is produced, which mostly takes place in the Xinjiang region. Given that it is expected that quartz mining will take place close to the MGS smelters, and many MGS smelters own their own quartz mine (to ensure reliable raw materials supply), only the MGS smelters are included in the S-LCA. For the E-LCA, the extraction of quartz is also included.

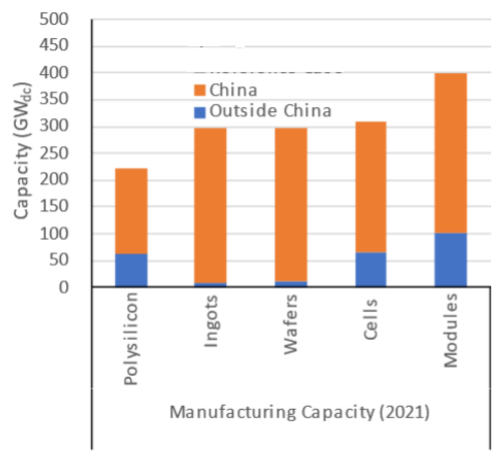


Figure 4.3: PV manufacturing capacity inside and outside China (taken from U.S. Department of Energy (2021) [7])

Metallurgical-grade silicon

Then the high-grade quartz is converted into metallurgical-grade silicon (MGS) by removing the oxygen. This is an energy intensive process since the electric arc furnace requires 10 – 15 MWh of power for each ton of produced MGS. Since MGS represents a relatively low economic value, the involved production costs should also be as low possible. This means that the location of MGS is often in regions where there is an abundant amount of cheap electricity and labor. Table 4.3 shows the Chinese PV manufacturing by component and province [7]. This table demonstrates that (1) China has a 70% share in global MGS production; and that (2) 38% of the Chinese MGS is produced in the Xinjiang province, 20% is produced in Yunnan, 17% is produced in Sichuan, and 4.5% is produced in Inner Mongolia. Furthermore, huge MGS capacity increases are announced in the Inner Mongolia province. The Yunnan and Sichuan provinces are mostly relying on hydroelectricity, while the Xinjiang and Inner Mongolia regions are dominated by thermal-based electricity as indicated in Figure 4.4. More concretely, Figure 7.3 shows that this thermal-based electricity is often realized by coal-fired plants in the Xinjiang region [7], [31], [Appendix: solar supply chain expert]. In summary, although there is a lack in supply chain transparency, it is expected that many MGS producers are located in the Xinjiang region. This concretely means that the E-LCA assumes that the MGS production takes place in the Xinjiang region, and will therefore assume that the MGS production is based on coal-fired electricity.

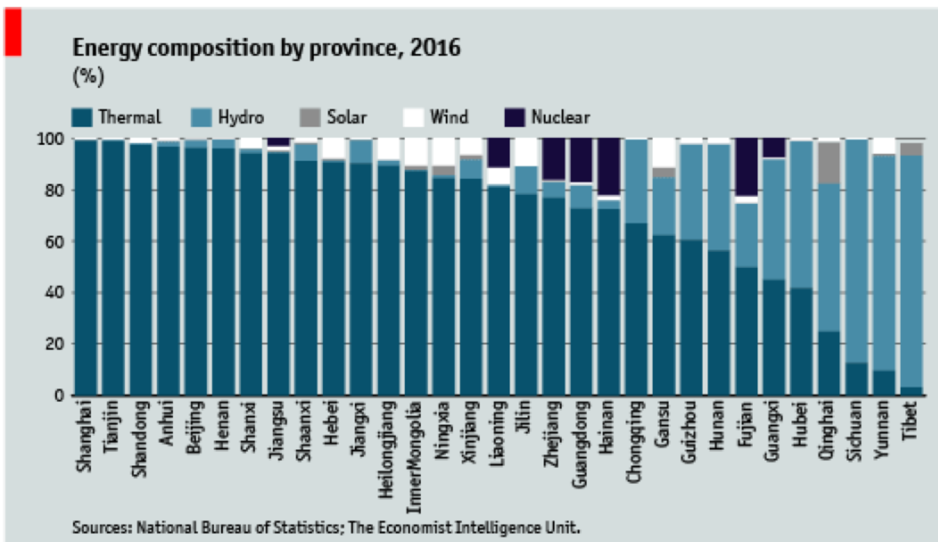


Figure 4.4: Energy mix in Chinese provinces

The company with the highest MGS production capacity is Hoshine Silicon Industry which generates around 52% more than the cumulative capacity of its nine main competitors (in total around 498,500 tons per year) [31]. This company has participated in a wide variety of sponsored incentives programs from the Chinese government [31]. The People's Republic of China (PRC) introduced these so-called "labor transfer" and "surplus labor" programs to alleviate poverty, especially in Xinjiang [31]. This, however, does not automatically mean that MGS produced outside Xinjiang cannot be linked to these "labor programs". For example, in case the MGS is produced in Yunnan or Sichuan (mostly relying on hydroelectricity), drought can result in a electricity shortage meaning that the power should come from the Chinese grid. In the past three years, China encountered many dry periods. However, historically, the plant is shut down since it is too expensive to operate. So if this plant is shut down, it is likely that the MGS is bought from producers that does not rely on hydropower (e.g., Xinjiang). Therefore, it is expected that MGS producers outside Xinjiang somethimes buy MGS from Xinjiang in case of shortages [Appendix: solar supply chain expert]. It is assumed that Hoshine is part of the supply chain identification since this company supplies indirectly to JA Solar (will be explained later in this chapter) and will therefore be considered in the S-LCA.

Polysilicon

Once the quartz has been converted into MGS, it is required to further purify this even more into polysilicon. Many alternative technologies can be used to create this polysilicon, but more than 90% of it is produced by using the Siemens process. This process is commonly used because it yields the higher-purity polysilicon required for the highly efficient monocrystalline cells. This Siemens process requires high temperatures making it an energy-intensive stage. Given that there is an abundant amount of cheap coal in the Xinjiang region, makes this province an ideal location for the polysilicon production. However, not only the low electricity prices was the reason for moving to this region, also the "labor transfer" and "surplus labor" programs lowered the labor costs. Many businesses were encouraged to build facilities in the Xinjiang region due to these government incentives. This is apparent from the fact that the four biggest polysilicon producers in Xinjiang dominates the global polysilicon production with a share of 45% [31] [37]. This share of 45% might suggest that only 45% of the PV modules can be related to Xinjiang. However, polysilicon producers outside Xinjiang can still buy MGS from producers in Xinjiang. Note, it is expected that the polysilicon production will increase significantly in Inner Mongolia and slightly decrease in Xinjiang [31] [Appendix: solar supply chain expert].

Currently JA Solar is supplied by five main polysilicon producers and its suppliers are shown in Table 4.1 (based on interview with solar supply chain expert). This table shows that the main suppliers of JA Solar are: (1) Asia Silicon (based in Qinhai) Xinte (based Urumqi and Xinjiang), Daqo (based in Xinjiang), Xinte (based in Inner Mongolia), and GCL-Poly (Xinjiang) [7], [Appendix: solar supply chain expert]. Among other have Daqo and GCL-Poly declared their involvement in labor transfer or labor placement programs or are sourced from MGS suppliers who have [31]. Also Daqo, which is one of the polysilicon supplier of JA Solar, is supplied with MGS coming from Hoshine (involved with labor programs) [31], implying that there is a high chance of social risks. Daqo claimed that it had received subsidies for "labour placements" from the Chinese government which may indicate that it uses state-sponsored labor transfers in its own facilities since this term is often used by the central government that imply for labour transfers. Only Daqo supplies polysilicon to all four solar module manufacturers that has market share, including LONGI, JinkSolar, TrinaSolar, and JA Solar. In summary, two conclusion are drawn. First, it is assumed that Daqo is part of the supply chain identification since this company supplies directly to JA Solar and will therefore be included in the S-LCA. Second, given that the majority of the polysilicon supply to JA Solar is coming from the Xinjiang region, the E-LCA will incorporate coal-fired electricity for the polysilicon production.

Table 4.1: JA Solar- Polysilicon supply

Contract #	Poly supplier	Ton polysilicon	Start contract	Stop contract	Total months
1	Asia Silicon (Qinghai)	94,800	09-2020	09-2025	36
2	Xinte (Urumqi, Xinjiang)	97,200	10-2020	12-2025	63
3	Daqo (Xinjiang)	153,800	01-2021	12-2023	48
4	Xinte (Inner Mongolia)	Unknown	Unknown	Unknown	Unknown
5	GCL-Poly (Xinjiang)	Unknown	Unknown	Unknown	Unknown

Ingot, wafer, cell, and module

Then this polysilicon is melted and shaped into monocrystalline silicon ingots, which are in turn sliced into thin wafers. Then the wafers a converted through a sequence of wet and high-temperature chemical processes into cells. Finally, the cells are interconnected and sandwiched between glass and plastic sheets. An vertical integrated supply chain from the ingot to the module is common among the biggest Chinese PV module manufacturers (in terms of capacity), including JA Solar. Therefore, only JA Solar is considered in the S-LCA. Although JA Solar does not seem to be directly involved in any government-related programs in Xinjiang (in constrast with JinkoSolar and TrinaSolar) they can be affected through its suppliers (e.g., Daqo, Xinte, and GCL-Poly).

In contrast with the MGS and polysilicon production which mostly take place in one dominant province, the ingot, wafer, cell, and module production is more distributed across China, which can be seen in Figure 4.5 and Table 4.3. This figure shows that the majority of the ingot, wafer, cell, and module production is based in Eastern provinces due to easier access to global shipping and proximity to Chinese citizens. Also it can be concluded that the most dominant province for these processes is Jiangsu, which is just north of Shanghai. Although JA Solar is likely to be provided with ingots, wafers, and cells from other parties, this research only considers JA Solar in the supply chain to further limit the scope of the project. This means that the S-LCA only considers JA Solar for the ingot, wafer, cell, and module production. Furthermore, given that the production of the ingot, wafer, cell, and module are more distributed across China, the E-LCA applies the average Chinese electricity mix to model these processes. Refer to Table 4.2 for the composition of the different energy sources to the Chinese energy mix.

Table 4.2: Chinese electricity mix in 2020 (taken from IEA (2022) [10]

Source	**Share**
Coal	0.640666564
Natural gas	0.027957797
Hydro	0.171001533
Oil	0.001383401
Wind	0.060359669
Solar	0.034552107
Nuclear	0.046917913
Biofuel	0.017161016

In conclusion, the extensive adoption of labor programs by the Chinese government suggests that it is likely that a silicon-based PV module can contain at least a small amount of silicon that originated from Xinjiang. Although the Xinjiang province contributes most to the MGS and polysilicon production capacity, this does not imply that producers outside Xinjiang cannot be linked to this region since they can still purchase raw materials or MGS that originate from Xinjiang. Thus, the reach of Xinjiang in much wider than only the companies that are based in this region. This concretely means that the S-LCA includes Hoshine (MGS production), Daqo (polysilicon production), and JA Solar (for the ingot, wafer, cell, and module production). Furthermore, the E-LCA considers coal-fired electricity for the MGS and polysilicon production, while the average Chinese electricity mix is incorporated for the ingot, wafer, cell, and module production.

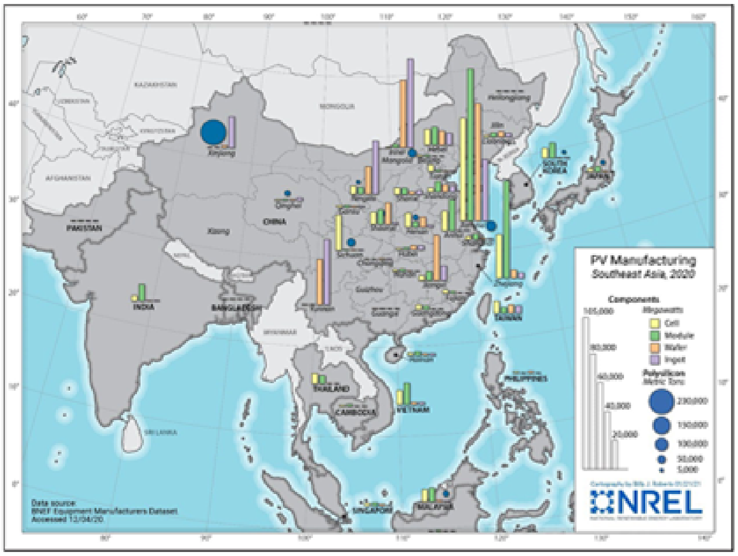


Figure 4.5: PV manufacturing in Southeast Asia in 2020 (taken from U.S. Department of Energy (2021) [7])

Table 4.3: Chinese PV manufacturing by component and province [7]

Province Rank in China	**Quartz ***	**MGS**	**Polysilicon**	**Ingots**	**Wafers**	**Cells**	**Modules**
1		Xinjiang	Xinjiang	Inner Mongolia	Jiangsu	Jiangsu	Jiansu
2		Yunnan	Inner Mongolia	Yunnan	Yunnan	Zhejiang	Zhejiang
3		Sichuan	Jiangsu	Ningxia	Inner Mongolia	Sichuan	Anhui
4		Inner Mongolia	Sichuan	Jiangsu	Jiangxi	Shaanxi	Hebel
5			Qinhai	Sichuan	Ningxia	Henan	Jiangxi
Chinese Fraction of Global Manufacturing Capacity		75%	72%	98%	97%	81%	77%
Top-5 Provinces Fraction of Chinese Manufacturing Capacity		80%	93%	83%	81%	80%	84%
Top-5 Provinces Fraction of Global Manufacturing Capacity		60%	67%	81%	78%	65%	64%

* much unknown and high level of uncertainty

Chapter 5

Social LCA Results

5.1 Impact Assessment

This chapter presents the S-LCA impact assessment results after which these are interpreted. The goal of this chapter is to identify the stakeholder group (and thus the life cycle stage) where the chance on social impacts is the biggest (=social hotspots). Each individual indicator is provided with a narrative to help in understanding the indicator score. Then, these results are interpreted to identify the stakeholder groups that are most impacted within the considered system boundaries.

Stakeholder group: Worker – MGS & Polysilicon

As discussed in chapter JA Solar is supplied with polysilicon by Daqo which in turn is supplied by MGS by Hoshine. Therefore, the intention was to represent both the Hoshine and Daqo workers in the S-LCA. Chapter 4 demonstrated that a major part of the global MGS and polysilicon is produced in Xinjiang which is a large province in the northwest of China with many industrial activities. It appears that this region accounts for 38% of Chinese MGS production and 40% of global polysilicon production. In 2017 the office of the UN High Commissioner for Human Rights (OHCHR) received an allegation that people from the Xinjiang region were missing or were disappeared from this region. It turned out that the Chinese government introduced "labor programs" with the idea to counter terrorism, as well as promote development, create jobs, and alleviate poverty. Hoshine declared that they participated in these labor programs and they are also indications that Daqo is involved with these programs. The OHCHR has carefully examined this situation by reviewing and analyzing accessible official documentation, as well as research materials, satellite imagery, and open-source information. Also, detailed interviews were conducted with citizens who were employed by these government programs. Both this research and report from the Sheffield University were used for assessing this stakeholder group [32], [31].

Table 5.1 shows the results for the worker during MGS and polysilicon production. Based on this table it can be concluded that this stakeholder group is likely to be subjected to forced labor and other social impact categories. Since the MGS and polysilicon are expected to take place in the Xinjiang region, the involved workers are likely to experience these labor transfers. These labor transfers have a persistent threat of detention and re-education and the workers are often unable to refuse or walk away from these jobs. Although the data was collected by official documents, Table 3.4 revealed that the used data had an appropriate level of representativeness meaning that the outcomes are relatively reliable.

Table 5.1: S-LCA results for the worker (during MGS and polysilicon production) stakeholder group

Indicator value 1 = in line with desired direction
Indicator value 0 = opposite with desired direction
Indicator value 0.5 = value of half of the companies comply with the desired direction

Indicator #	Indicator name	Indicator value	Indicator narrative	Source
1	Right of workers to join organizations of their choosing	0	The so-called "surplus-labor" has linkages to forced labor and enslavement since many indigenous worker are unable to reject or quit from these jobs. The freedom of employment choice guaranteed by Article 23 of UN Declaration of Human Rights is violated by these programs.	[31], [32]
2	Employment is not conditioned by any restrictions on the right to collective bargaining	0		
3	Presence of child labor	1	No examples were found that indicated to the involvement of child labor.	[31], , [32]
4	Presence of unpaid labor	0	People working for these programs have experienced unpaid labor, paid for less than the minimum wage, or have their salaries lowered under the pretext that the employees owe their employers money for food or transportation to work,.	[31]
5	Involvement of known and regular payment	0		
6	Presence of unclear wage deductions	0		
7	Employees are paid at least by the legally mandated minimum wage	0		
8	Compliance with legal rules for working hours	1	Daqo and Hoshine declare to abide the Labor Law and the Labor Contract Law of the People's Republic of China. This implies that this company complies the legal rules for working hours and pause periods.	[38], [39]
9	Compliance with legal rules for pause periods	1		
10	Compliance with legal rules for leave of absence	1	The holiday benefits for the employees are in compliance with legal holidays.	[38], [39]
11	Employees are covered by health insurance	1	Hoshine ensures that these themes are covered since they abide the national laws. Daqo explicitly reports that employees are covered by social insurance; for example, pension insurance, medical insurance, work injury insurance, maternity insurance, unemployment insurance.	[38], [39]
12	Employees are covered by retirement insurance	1		
13	Presence of a formal policy concerning health and safety	0.5	Although Daqo passed the certification of the ISO45001 Occupational Health and Safety Management Systems, Hoshine did not introduce any health and safety policy.	[38], [39]
14	Employees that can consistently use appropriate safety equipment	0.5		
15	Employees getting training and educated if needed before starting with working activities	0.5	Daqo claims that all employees have followed the necessary training before starting the working activities. On the other side, Hoshine did not mention anything about training for employees.	[38], [39]
16	Presence of human rights lawsuits against the company	1	No human rights lawsuits against Daqo or Hoshine were discovered. However, the USA has introduced a policy that bans imports of materials from Hoshine due to forced labor concerns. The European Union is not considering this kind of policy so far.	[40]
17	The organization has pledged to comply with the global compact principles and has engaged itself to present yearly	0	Both Hoshine and Daqo has not pledged itself to comply with the global compact principles.	[38], [39]
18	Presence of explicit code of conduct that protect human rights of workers among suppliers	0.5	Hoshine has not introduced a code of conduct, while Daqo has adopted several supplier assessment initiatives. This include requirements that define the employee rights (e.g., prohibition of forced labor, prohibition of child labor), safety considerations (e.g., strictly abiding national laws, ensuring safe working environment), and requirements that ensures that the ISO 14001 environmental management system certificate is passed.	[38], [39]
19	Presence of abuse of vulnerability	0	Millions of indigenous Uyghur and Kazakh natives from the Xinjiang region have been enrolled in "labor transfer" and "surplus labor" programs. Considering that these indigenous people are enrolled in these programs suggests that these populations are especially vulnerable to abuse and is more often found in forced labor.	[31], [32]

Table 5.1 continued

Indicator #	Indicator name	Indicator value	Indicator narrative	Source
20	Presence of deception	0	Examples are known where people were coerced into working in factories while this was not agreed upon on. This is an example that indicates that these "labor transfer" is involved with deception.	[31], [32]
21	Restriction of movement	0	Many workers involved in these programs are unable to decline or quit from these jobs and frequently cannot leave the workplace voluntarily.	[31], [32]
22	Isolation	0	At least 135 camps (where employees are living) are identified that are closely based near to remote factories. This together with the fact that these workers are not free the leave the workplace and living area indicates that there is a presence of isolation.	[31], [32]
23	Physical and sexual violence	0	Stories are known involving several young women who were distraught knowing that they had to leave their family to go work thousands miles away. To convince these women, government officials and labor agents harassed the women for days and promised them to return to home at any time with great wealth.	[31], [32]
24	Intimidation and threats	0	Evidence suggests that these "labor transfers" in the Xinjiang region occur under coercion conditions, supported by the ongoing threat of re-education and internment.	[31], [32]
25	Retention of identity documents	0	There are cases where workers in these factories are retained from their identification cards and are constantly controlled by their movement by local police.	[31]
26	Withholding of wages	0	People working in the camps frequently encounter either unpaid, paid less than the minimum wage, or have their salaries lowered (with the explanation that the employees owe their employer money for food or transportation.	[31]
27	Debt bondage	0		
28	Abusive working and living conditions	0	Many of the factories where employees are employed are surrounded by razor-wire fences, gates, surveillance cameras and are controlled by police or security.	[31], [32]
29	Excessive overtime	Unknown	Nothing was found regarding working hours.	
30	Presence of formal policies on equal opportunities	0.5	Daqo aims to ensure equal opportunities by insisting this in the recruitment process. On the other hand, Hoshine has not addressed this topic in their policy.	[31]
31	Presence of formal policies on combating discrimination	0.5	Daqo abide all labor related laws, which imply that any form of employee discrimination is prohibited; however, Hoshine has not included this in their policy.	[38], [39]
32	Presence of any form discrimination incidents	0	Within the Xianjinag region, there is discrimination on ethnic grounds in (mostly Uyhur and Muslim communities).	[31], [32]
33	Presence of a written contract that defines the relationship between the employer and workers (rights and responsibilities)	Unknown	Nothing is reported about this theme.	
34	Presence of sexual harassment incidents	1	Refer to indicator #23	[31]
35	Existence of clear responsibilities for matters of sexual harassment within the organization	0.5	Daqo explicitly reports that it prohibits any form of sexual harassment in the workplace. Hoshine has not mentioned responsibilities in terms of this theme.	[38], [39]
Average		**0.33**		

Stakeholder group: Worker – Ingot, Wafer, Cell, and Module

Table 5.2 presents the outcomes for the Ingot, Wafer, Cell, and Module worker. To date, no evidence of forced labor has been found in Chinese PV module factories [41]. To represent the worker during the ingot, wafer, cell, and module production, a questionnaire was sent to JA Solar in which themes such as working conditions and human rights are central. In addition, the sustainability report of JA Solar was also used for assessing potential social impacts. Table 5.2 shows that no social impacts were discovered. However, considerable attention must be paid when interpreting these results. As mentioned in Chapter 3.3.2, it is unlikely that the used inventory meets the data quality requirements to appropriately reflect this stakeholder group. This was also confirmed during interviews with the Dutch embassy and the solar supply chain expert since both parties insisted to attach no value on the outcomes of the questionnaire. Thus, although no impacts were discovered, it is hard to conclude on this stakeholder group since the used inventory lack in meeting the data quality requirements.

Table 5.2: S-LCA results for the worker (during ingot, wafer, cell, module production) stakeholder group

Indicator value 1 = in line with desired direction
Indicator value 0 = opposite with desired direction

Indi-cator #	Indicator name	Indicator value	Indicator narrative
1	Right of workers to join organizations of their choosing	1	No forced labor is accepted in any form (e.g., violence, threat, or illegal restriction of personal freedom) and is incorporated in policies. This suggests that all employees joined the organization of their own choosing.
2	Employment is not conditioned by any restrictions on the right to collective bargaining	1	The legal rights of the employees are protected; for example, the right to free association and collective bargaining is respected for all employees.
3	Presence of child labor	1	No child labor is involved as all employees must meet the age requirements based on local laws and regulations.
4	Presence of unpaid labor	1	Policies are in place to ensure that all employees are paid at least the minimum wage required by law. Therefore it is assumed that all employees receive their wages at known and regular intervals and that wages according to the contract are also paid structurally.
5	Involvement of known and regular payment	1	
6	Presence of unclear wage deductions	1	
7	Employees are paid at least by the legally mandated minimum wage	1	
8	Compliance with legal rules for working hours	1	A collective labor agreement was signed to safeguard the rights and interests of employees in relation to payments, working hours, pauses and vacations, occupational safety and health, insurance benefits, and career development. Furthermore, China is also revising its legislation to improve workplace safety and Working Hours Act to address structural overtime.
9	Compliance with legal rules for pause periods	1	
10	Compliance with legal rules for leave of absence	1	
11	Employees are covered by health insurance	1	
12	Employees are covered by retirement insurance	1	
13	Presence of a formal policy concerning health and safety	1	The ISO 45001, ISO 14001, and SA8000 systems, as well as local laws and regulations are adopted to ensure health and safety of employees during operations. Also safety equipment is consistently available.
14	Employees that can consistently use appropriate safety equipment	1	
15	Employees getting training and educated if needed before starting with working activities	1	A total of 440,000 employees received safety training. This means that many forms of training was provided to improve the safety skills of the employees, such as instruction on firefighting equipment, transportation safety, electrical safety, and fire drills.
16	Presence of human rights lawsuits against the company	1	No recent lawsuits were found.
17	The organization has pledged to comply with the global compact principles and has engaged itself to present yearly	1	All of the UN Global Compact's Sustainable Development Goals (SDGs) are addressed.
18	Presence of explicit code of conduct that protect human rights of workers among suppliers	1	In order to incorporate environmental, social, moral, health, and human rights considerations in procurement decision-making, sustainable procurement rules have been introduced. Additionally, it is also required by some cores suppliers to provide paperwork for inspection, such as a sustainability report and an internal code of conduct.
19	Presence of abuse of vulnerability	1	The legal rights of the employees are protected by strongly disapproving any form of violence, forced labor, threats, or illegal restriction of personal freedom. Besides, legal rights are also protected in the following areas: freedom of belief, gender equality (with equal pay for the same work), and no discrimination based on ethnicity, race, nationality, religious belief, gender, age, disability, etc.
20	Presence of deception	1	
21	Restriction of movement	1	
22	Isolation	1	
23	Physical and sexual violence	1	
24	Intimidation and threats	1	
25	Retention of identity documents	1	

Table 5.2 (continued)

Indicator #	Indicator name	Indicator value	Indicator narrative
26	Withholding of wages	1	Fundamental rights and interests are protected for all employees, implying that these no wages are withhold and no debt bondage is present.
27	Debt bondage	1	
28	Abusive working and living conditions	1	Intended to set up a joyful working environmental; for example, by creating a reading area, organizing team building activities, or setting up sports events.
29	Excessive overtime	1	Local labor laws apply and is also enforced by authorities, suggesting that chance of excessive overtime is relatively low.
30	Presence of formal policies on equal opportunities	1	Policies are in place to ensure equal opportunities and to combat any form of discrimination.
31	Presence of formal policies on combating discrimination	1	
32	Presence of any form of discrimination incidents	1	No discrimination incidents were reported.
33	Presence of a written contract that defines the relationship between the employer and workers (rights and responsibilities)	1	Every employee is provided with a written employment agreement in a language they understand.
34	Presence of sexual harassment incidents	1	No incidents regarding sexual harassment were reported.
35	Existence of clear responsibilities for matters of sexual harassment within the organization	1	This is explicitly mentioned in the Code of Conduct.
Average		**1**	

Stakeholder group: Worker – Installation

Table 5.3 shows the results for the worker stakeholder group related to the installation of solar panels. Practically all installers are contracted through a subcontractor and the majority of these workers come from East-European countries, such as Bulgaria and Poland. Especially these migrant workers are more vulnerable to abuse since most of these people lack knowledge of the local language and laws, have only one livelihood option, and may belong to a minority religious or ethnic group. The used inventory to assess this stakeholder group was obtained by directly interviewing the workers and also people from the management of these companies. Even though most of the installation parties haven't proclaimed any policy regarding working conditions or human rights, no social impacts have been identified for this stakeholder group. However, it is recommended to pay extra attention to monitor the working times of the installers. Even though the working hours comply with national legislation, these hours are close to the maximum permitted by law. In summary, based on an appropriate level of representativeness (indicated in Table 3.4), it can be concluded that there is a low chance of social risks during the installation stage.

Table 5.3: S-LCA results for the worker (during installation) stakeholder group

Indicator value 1 = in line with desired directio;
Indicator value 0 = opposite with desired direction

Indicator #	Indicator name	Indicator value	Indicator narrative
1	Right of workers to join organizations of their choosing	1	Each employee chooses to work for the organization of their own choice. The majority of employees joined the company through a recruitment agency and are from East European nations (e.g., Poland, Bulgaria).
2	Employment is not conditioned by any restrictions on the right to collective bargaining	1	Although there are often guidelines in the collective labor agreement, there is still room for negotiation.
3	Presence of child labor	1	It is not anticipated that child labor would be present during the installation phase since it occurs in the Netherlands. Other than some students that work on internship assignments, no instances of child labor were discovered.
4	Presence of unpaid labor	1	No issue has arisen with payments (deposited to the bank accounts) in the last ten years.
5	Involvement of known and regular payment	1	All employees receive payment on a structural and known basis.
6	Presence of unclear wage deductions	1	No wage deductions have been experienced.
7	Employees are paid at least by the legally mandated minimum wage	1	Laws at the national level apply to all workers, guaranteeing that they are paid with the legally mandated minimum wage.
8	Compliance with legal rules for working hours	1	It is intended to work between 8 and 8.5 each day, six days a week. Although it complies with national laws, this should carefully be monitored because this amount of hours is close to the legally allowed worked hours.
9	Compliance with legal rules for pause periods	1	Every employee has the right to a break during a work day, which is often between 12:30 and 1:30 p.m.
10	Compliance with legal rules for leave of absence	1	The number of days off that employees can take (24 days) is in accordance with national laws (minimum 20 days).
11	Employees are covered by health insurance	1	Yes.
12	Employees are covered by retirement insurance	1	Yes.
13	Presence of a formal policy concerning health and safety	0	The majority of the installation parties haven't included policies regarding public health and safety policy despite all of them declaring that they ensure appropriate working conditions.
14	Employees that can consistently use appropriate safety equipment	1	All employees wore the obliged safety shoes, helmets, and vests during the site inspections.
15	Employees getting training and educated if needed before starting with working activities	1	Before starting the working activities, the necessary (safety) instructions are explicitly communicated. For example, at the start of every new project the allowed smoking areas and the sanitary areas are communicated.
16	Presence of human rights lawsuits against the company	1	No.
17	The organization has pledged to comply with the global compact principles and has engaged itself to present yearly	0	No.
18	Presence of explicit code of conduct that protect human rights of workers among suppliers	0	No.

Table 5.3 continued

Indicator #	Indicator name	Indicator value	Indicator narrative
19	Presence of abuse of vulnerability	1	People who lack the local language or laws, or who have only a few options for livelihood, are particularly vulnerable to abuse and more likely to be found in forced labor [42]. Since the majority of the employees can't speak Dutch nor English and only have on likelihood options, these group of people have a higher chance to be subjected of this type of forced labor. However, the lead of the employees speaks English so there is always a translator available for the employees. Additionally, all of the interviewed employees expressed their satisfaction with the housing facility.
20	Presence of deception	1	The failure to fulfill verbal or written promises made to employees is defined as deception. This is not identified during interviews since all employees are informed in their home country about, for example, working activities, salary, working hours, and housing facilities.
21	Restriction of movement	1	If workers are not free to enter or quit the workplace, subject restrictions that deemed fair, this can be a clear sign of forced labor. In this case, all employees are completely free to enter and exit both work and housing facilities. They have one month to provide notice if they choose to resign.
22	Isolation	1	Forced labor victims are frequently facing isolation in remote locations and are forbidden to access the outside world. The workers are often based in vacancy parks, allowing them to interact with locals or other residents.
23	Physical and sexual violence	1	There were no incidents of physical or sexual abuse.
24	Intimidation and threats	1	People who are subjected to forced labor and who protest their conditions or want to resign may face threats or intimidation. One instance was mentioned in which a worker was fired after neglecting multiple warnings. This is, however, not any form of intimidation.
25	Retention of identity documents	1	The retention of identity documents or other valuable personal possessions by the employer may be an indication of forced labor since this can place the employee in a vulnerable position. However, this was not the case for the considered installers, as all employees had constant access to their identification documents and other valuable items.
26	Withholding of wages	1	When wages are routinely and consciously withheld in order to keep a person from leaving and prevent them from switching employers, this may indicate forced labor. The employees who were interviewed always received regular payments and have not encountered such situations.
27	Debt bondage	1	This concept can be defined if workers are trying to pay off debts to the employer. This was also not experienced by any of the employees.

Table 5.3 continued

Indi-cator #	Indicator name	Indicator value	Indicator narrative
28	Abusive working and living conditions	1	Work may be done in hazardous (without adequate protective equipment) or degrading (humiliating or dirty) environments. Additionally, overcrowded and unhealthy living conditions without any privacy are examples of abusive living conditions. In general, the workers expressed satisfaction with their living and working environments. One worker mentioned: "since two or three years ago, a lot has changed. Five years ago, not everyone had a room of their own, but today, everyone does and the rooms are comfortable."
29	Excessive overtime	1	The working hours are consistent with national laws.
30	Presence of formal policies on equal opportunities	0	No.
31	Presence of formal policies on combating discrimination	0	No.
32	Presence of any form of discrimination incidents	1	No discrimination examples were mentioned during the interviews.
33	Presence of a written contract that defines the relationship between the employer and workers (rights and responsibilities)	1	Yes. All employees signed a contract before starting with the working activities.
34	Presence of sexual harassment incidents	1	No. This was never experienced by the employees.
35	Existence of clear responsibilities for matters of sexual harassment within the organization	0	No.
Average		**0.83**	

Stakeholder group: Local community

Table 5.4 shows the results for the Chinese local community stakeholder group. The used inventory was based on the sustainability reports of JA Solar, Daqo, and Hoshine and complemented with web research with search terms related to the indicator names. The greatest social impact for this stakeholder group is expected with regard that no policy being implemented to protect indigenous community members. Furthermore, local people can as result from the working activities of Hoshine and Daqo experience involuntary relocating. Given that these findings are based on a limited extent of representativeness (indicated in Table 3.4), the results from this analysis should be treated with utmost caution. This makes it unfeasible to concretely conclude whether the local community stakeholder group is involved with social impacts.

Table 5.4: S-LCA results for the local community stakeholder group

Indicator value 1 = in line with desired direction
Indicator value 0 = opposite with desired direction
Indicator value 0.33 = value of one company is in line with desired direction
Indicator value 0.67 = values of two companies are in line with desired direction

Indicator #	Indicator name	Indicator value	Indicator narrative	Source
48	Presence of individuals that have experienced involuntary relocating that can be attributed to the organization	0.33	There are no cases of involuntary relocation that can be connected directly to JA Solar. However, the so-called "surplus labor" and "labor transfer" programs present in the Xinjiang region seems to imply that these initiatives are tanteamount to forced transfers of people. Both Hoshine and Daqo are likely to be involved in these practices.	[32], [31]
49	Evidence of policies/management plan(s) in place to protect and/or support cultural heritage	0.67	JA Solar and Daqo enhances the cultural life of its employees byplanning sports events, debates, knowledge competitions, and team-building exercises. Hoshine has not included such efforts in its management plan.	[33], [39], [38]
50	Presence of relevant organizational information to community members in their spoken language(s)	1	All company news is provided in both Mandarin and English	[33], [39], [38]
51	Presence of policy to protect the rights of indigenous community members	0	Concrete policy is missing.	[33], [39], [38]
52	Presence of documented illegal activities	1	No cases were found that connected any illegal activities.	Source
53	Organization commitment to accept indigenous land rights	0	Concrete policy is missing.	
54	Number of legal complaints per year against the organization with regard to security concerns	1	No examples were found.	Source
55	Presence of policy to minimize hazardous substances	0.67	Policy has been introduced by only JA Solar and Daqo that handle toxic and hazardous substances and are in conformity with local laws and regulations.	[33], [39], [38]
56	Presence of rare material resource use due to product design decisions	1	The solar industry is not dependent on rare earth elements, in contrast to the wind energy indsutry and electric vehicle sectors (due to materials needed for making the magnets). Instead, a variety of metals, such as silicon, indium, gallium, selenium, cadmium, and tellurium, are used in solar cells.	[43], [44]
57	Product or technology design makes use of local resources and expertise	1	JA Solar sector is mostly relying on other Chinese suppliers (e.g., Daqo, Hoshine, Xinte, GCL-Poly)	Chapter 4
Average		**0.67**		

Stakeholder group: Society

Table 5.5 presents the results for the Chinese society stakeholder group. The used inventory is based on the sustainability reports from Hoshine, Daqo, and JA Solar and is complemented with desk research. The solar industry is expanding as more renewables are incorporated into the energy mix. Over USD 30 billion was exported from China to other countries all over the world, accounting for nearly 7% of the country's five-year trade surplus [45]. The numbers are consistent with rising RD expenditures, efficiency improvements, and revenue increases. However, for this stakeholder group, the main social risk is posed by China's relatively high corruption perception index and the involvement in corruption by JA Solar quite recently. Corruption has the potential to erode trust by society in the public sector and it can also waste taxes that were initially allocated to, for example, important community projects. Also, this stakeholder group is represented by inventory with low data quality characteristics which implies that concluding on social impacts is unfeasible.

Table 5.5: S-LCA results for the society stakeholder group

Indicator value 1 = in line with desired directio;
Indicator value 0 = opposite with desired direction
Indicator value 0.33 = value of one company is in line with desired direction
Indicator value 0.67 = values of two companies are in line with desired direction

Indicator #	Indicator name	Indicator value	Indicator narrative	Source
59	Presence of public agreement to sustainability using the selected technology	1	China aims to reach carbon neutrality by 2060 and reach a peak in greenhouse gas emissions in 2030. To accomplish these goals, photovoltaics is considered a necessary component to replace fossil fuels. This is apparent from the 14th Five-Year Plan in June 2022, where it is stated that 33% of the power generation should be realized with renewable sources. This aim includes a target of 18% for wind and solar technologies.	[10], [46]
60	Presence of protests to the proposed technology	1	After demonstrations, a Chinese solar panel manufacturer closed in 2011, while also anti-pollution protests against solar panel manufacturer in Quanzhou and Fujian was present. In recent years, no protests have been reported.	[47], [40]
61	Partnerships in research and development	0.67	JA Solar and Daqo established intensive partnerships with domestic and international universities and research centers to investigate and develop innovative technologies and speed up industrialization. Hoshine has not mentioned anything on this theme.	[33], [39], [38]
62	Investments in research and development	0.67	JA Solar made significant investments in R&D, as seen by their 1.5 million USD, 2.0 million USD, and 3.7 million USD expenditures between 2019 and 2022. Daqo invested also in R&D, without mentioning any numbers. Hoshine has not made any reference of this subject.	[33], [39], [38]
63	Existence of technology efficiency improvement over years	1	The average commercial silicon module's efficiency rose from 15% to 20% and beyond over the past ten years.	Source
64	Presence of revenue growth of the organization	1	Revenue growth of JA Solar in 2020 and 2021 compared to 2019 was 22% and 95%, respectively. Also Daqo realized a significant revenue growth in recent years. Although Hoshine has not reported anything on this subject, it is expected that Hoshine has also established a considerable revenue growth.	[33], [39], [38]
65	Formalized commitment of the organization to prevent corruption	0.67	JA Solar and Daqo tackles this by running anti-corruption advocacy campaigns and this theme is also included in the management approach disclosures. Hoshine has not included this is its policy.	[33], [39], [38]
66	Acceptable level of corruption perception index	0	China receives a score of 45/100, indicating that while there has been progress over time, there is still a high likelihood of corruption.	[48]
67	Involvement of company in corruption or other unethical practices	0.67	In 2020, JA Solar was involved in corruption practices and chairman of JA Solar was detained by anti-corruption authorities from China. Nothing was found related to this theme for Hoshine and Daqo.	[49]
68	Formalized commitment of the organization to reduce poverty	1	JA Solar funded an initiative to fight poverty with 7.6 million USD. The objective of this project is to reduce poverty through industrial development, the production of renewable energy, and ecological improvement. Also Daqo introduced measures to reduce poverty. Hoshine has not included this in their documentation.	[33], [39], [38]
Average		**0.70**		

Stakeholder group: Children

Table 5.6 shows the results for the children stakeholder group. To ensure the same welfare and well-being for the future generation as the current generation, this stakeholder group was added. Although several projects have been launched by our supplier to enhance children's health and education, China falls short in providing equitable access to education, particularly in rural areas. Since the MGS and polysilicon processes take place in rural areas, there is a risk that the children living in the Xinjiang region lack in receiving equitable access to education. Furthermore, it seems that there is no child labor within the considered system boundary. Since the used inventory lack in realizing an appropriate level of representativeness, the S-LCA results for this stakeholder group might be unreliable. Again, additional (site-specific) data collection is required, as well as a larger range of indicators to determine more exactly possible social impacts for this stakeholder group.

Table 5.6: S-LCA results for the children stakeholder group

Indicator value 1 = in line with desired direction
Indicator value 0 = opposite with desired direction
Indicator value 0.67 = values of two companies are in line with desired direction

Indicator #	Indicator name	Indiator value	Indicator narrative	Source
69	Presence of stimulating measures to enhance education systems to communities	0.67	Education is a crucial human right and is preserved in the Universal Declaration of Human Rights (1948). This is also acknowledged by JA Solar since they formally started a program that aimed to build schools and provide education in poor areas. Daqo donated more than 1 million USD to stimulate children development. Hoshine has not mentioned anything.	[33], [39], [38]
70	Presence of equitable access to education	0	With an estimated 279 million children between 0 and 17, China is responsible for educating a massive amount of children. Access to education has greatly grown during the last decades, but challenges remain. The education that each child receives varies in quality; for example, children in rural communities notably lack access to high-quality education. Furthermore, there are also inequities based on location, wealth, and migration status.	[50]
71	Formalized commitment of organization to improve the health of children	0.67	This indicator represents the contribution of a solar panels to the health of children as consumers. JA Solar launched a project that attempts to regularly support medical assistance for poor patients. Also Daqo introduced measure to promote health of children. Hoshine has not mentioned anything on this theme.	[33], [39], [38]
72	The organization has a policy on responsible marketing	1	For products that might impact children's physical or mental health, responsible marketing should be considered. Since it is anticipated that solar panels only benefit children's physical health and have no negative effects on their mental health, there is no risk that marketing will harm children's health.	[33], [39], [38]
Average		**0.58**		

Stakeholder group: Consumer

Table 5.7 shows the results for the consumer stakeholder group and indicates that good social performance for the consumer stakeholder group is accomplished. The sustainability report of Greenchoice was used as inventory to measure the company-specific indicators. In terms of privacy and transparency, no social impacts were discovered. This is mainly avoided by the strict regulations in the Netherlands on these themes. Given the huge waste streams that will arise in the coming decades, the End of Life management must be set up properly. Recycling solar panels after their lifetime is heavily stimulated by European regulations, and is also extensively researched currently. Additionally, although it can be complex to reuse solar components from an economic perspective, yet the components of solar panels can be reused. It is plausible that several limitations may have influenced the results since the used inventory lack in realizing an appropriate level of representativeness. Therefore, care must be taken when concluding on the social impacts for this stakeholder group.

Table 5.7: S-LCA results for the consumer stakeholder group

Indicator value 1 = in line with desired direction;
Indicator value 0 = opposite with desired direction

Indi-cator #	Indicator name	Indicator value	Indicator narrative	Source
36	Availability of a mechanism where consumers can provide feedback	1	Greenchoice has a customer service available that is in charge of communicating with their clients. Via this end, customers can provide feedback.	[51]
37	Presence of an internal management system to protect consumer privacy	1	A cyber security system is implemented and further rolled out, together with education and e-learnings for employees	[34]
38	Presence of consumer complaints related to breach of privacy or loss of data within the last year	1	The most recent data leak was discovered in June 2021, and measures have been taken to address and solve the issue.	[52]
39	Presence of management measures to assess consumer health and safety	1	It is believed that people who utilize solar panels don't have any health concerns. In fact, it is considered that its application is only beneficial for people's physical health. Nevertheless, actions have been taken to prevent data loss, the backup strategy has been reviewed, and investments were made to tackle vulnerabilities in the operating system.	[34]
40	Presence of a quality and/or product safety management system such as ISO	1	To ensure health and safety considerations, the ISO 45001 system is used as a management framework. Furthermore, no incidents were reported of non-compliance regarding the health and safety of products.	[34]
41	Possibility of technology components to be reused or recycled for other purposes	1	Regardless of the technology employed, most of the PV modules on the European market can be disposed. The majority of a solar module's parts, including glass, cells, and metals, can be recycled.	[53]
42	Presence and quality of infrastructure to responsibly d ispose of product components	1	By 2030 the global solar waste is estimated at 1.7 – 8 million kg tons, while in 2050 this amount is expected to reach 60 – 78 million kg tons. These significant numbers denote the importance of developing an infrastructure that can manage these waste streams. The European Union holds solar developers accountable for their electronic waste and requires these companies to recycle. Improved recycling technologies have the potential to recover 85% (by weight) of silicon based PV modules.	[43], [10]
43	Presence of consumer complaints regarding transparency	1	No complaints were found in web search.	
44	Presence of public sustainability report	1	A sustainability report was released.	[34]
45	Electricity consumers have a choice in the utility company that will provide the technology	1	In the Netherlands, the customers have the free choice to decide on the energy provider. After a certain period of time, it is also allowed to switch among energy providers.	[54]
Average		**1**		

5.2 Interpretation

The objective of the research was to identify the environmental and social impacts of a PV module. Based on these identifications, it was intended to identify the environmental and social hotspots within the life cycle of a PV module.

This subchapter aims to conclude on the social hotspots within the supply chain of a typical PV module. This chapter presents the aggregated final indicator value for each stakeholder group, and is shown in Table 5.8. Note, a value of 0 would suggest a high risk of social impact, while a 1 would indicate that is a low risk of social impacts. This aggregated value is based on the arithmetic average of all indicators for each stakeholder group. This table shows that the main social hotspots are located during MGS and polysilicon production since this is the lowest value. Since the MGS and polysilicon production occurs mainly in the Xinjiang region, the workers are likely to be subjected to these labor transfers. Also companies (e.g., JA Solar) downstream in the supply chain run significant risks of having their supply chain affected by social impacts. The labor transfers for the indigenous people from the Xinjiang region imply clear indicators of human trafficking and forced labor, as defined by the International Labor Organization (ILO) [42]. The involved labor programs during the MGS and polysilicon production suggest indications of forced labor, such as, *abuse of vulnerability*, *deception*, *restriction of movement*, *isolation*, *intimidation and threats*, *retention of identity documents*, and *withholding of wages*, *debt bondage*. Also, the workers that perform the work are often unable to reject or quit their work, which further denotes the presence of forced labor.

Furthermore, Table 5.8 suggests that there is no risk of social impacts for the worker during ingot, wafer, cell, and module production. However, given that these results might be based on subjective inventory data obtained from JA Solar, limited value should be attached to these outcomes of the S-LCA. It is unlikely that these companies will admit any human right violations or poor working conditions. Because the relationship can be broken if the query reveals human rights violations or poor working conditions, JA Solar will be very careful about providing information on these topics. In addition, it seems that the filled questionnaire of JA Solar is also checked by the Chinese government.

Regarding the worker during installation, the S-LCA revealed that there is a relatively low chance of social risks for this stakeholder group. Given that the representativeness of the used inventory meets the requirements, it is expected that these outcomes are reliable. The results of the Chinese society, Chinese children, and Chinese local community stakeholder groups should be interpreted with utmost caution. This is mainly caused by a limited level of representativeness and a relatively small amount of used indicators to represent these groups. This makes that it cannot be concluded with certainty what the risk of social impacts is.

Last, Table 5.8 shows that there is no risk of social impacts for this stakeholder group. Although there is a limited level of representativeness, it is expected that this is not a hotspot within the considered system boundary. This was assumed due to the strict regulations in the Netherlands on privacy and transparency. Also, End of Life is heavily promoted by European regulations, implying that there is a small risk of social impacts for this stakeholder group.

In conclusion, when considering the representativeness of the inventory data, it can be concluded that the highest risk on social hotspots of the PV module is expected to occur during the MGS and polysilicon production. This is due that Table 5.8 revealed that this stakeholder group has the lowest aggregated indicator value.

Table 5.8: Final S-LCA results for each stakeholder group

Stakeholder group	**Life cycle stage**	**Average value**
	MGS & polysilicon	0.33
Worker	Ingot, wafer, cell, and module	1
	Installation	0.83
Local community	All manufacturing stages	0.67
Society	All manufacturing stages	0.7
Children	All manufacturing stages	0.58
Consumer	Use phase and EoL	1

Chapter 6

Environmental LCA Results

6.1 Impact Assessment

This chapter starts with presenting the life cycle impact assessment results, after which these are interpreted. Table 6.1 shows the environmental assessment per square meter of PV module for both the base case and the updated E-LCA. Note, the *base case* represents the E-LCA that uses only the Frischknecht et al. (2020) inventory, while the updated E-LCA reflects the thesis results.

Table 6.1: Numerical E-LCA results for base case and updated E-LCA

Impact category	Unit	**Base case**	**Updated E-LCA**
Agricultural land occupation	m^2/year	8.7	8.7
Climate change	kg CO_2-Eq.	102.3	108.0
Fossil depletion	kg oil-Eq.	26.3	27.8
Freshwater ecotoxicity	kg 1.4-DCB-Eq.	8.1	8.1
Freshwater eutrophication	kg P-Eq.	0.03	0.03
Human toxicity	kg 1.4-DCB-Eq.	36.3	37.0
Ionising radiation	kg U235-Eq.	6.1	6.6
marine ecotoxicity	kg 1.4-DCB-Eq.	7.4	7.4
Marine eutrophication	kg N-Eq.	0.004	0.006
Metal depletion	kg Fe-Eq.	35.9	36.0
Natural land transformation	m^2	-0.01	-0.01
Ozone depletion	kg CFC-11-Eq.	$9.0E^{-6}$	$9.7E^{-6}$
Particulate matter formation	kg PM10-Eq.	0.2	0.2
Photochemical oxidant formation	kg NMVOC-Eq.	0.4	0.5
Terrestrial acidification	kg SO_2-Eq.	0.4	0.5
Terrestrial ecotoxicity	kg 1.4-DCB-Eq.	0.03	0.03
Urban land occupation	m^2/year	1.1	1.2
Water depletion	m^3 water-Eq.	0.8	0.8

This figure demonstrates that by updating the energy mix and by adding the the transport and installation stages, the overall impacts are generally speaking, increased. In the remaining of this chapter, the individual categories are discussed in more detail, where the biggest contributors and possible measures are highlighted. Furthermore, Figure 6.1 shows a radar chart of the results allowing to conclude on the percentual change compared to the base case. It can be concluded that 8 out of the 18 impact categories changed with a minimum of 5% compared to the base case. Moreover, this figure demonstrates that in particular the following impact categories are changed: *Marine eutrophication*, *Particulate matter formation*, *Photochemical oxidant formation*, and *Terrestrial acidification*.

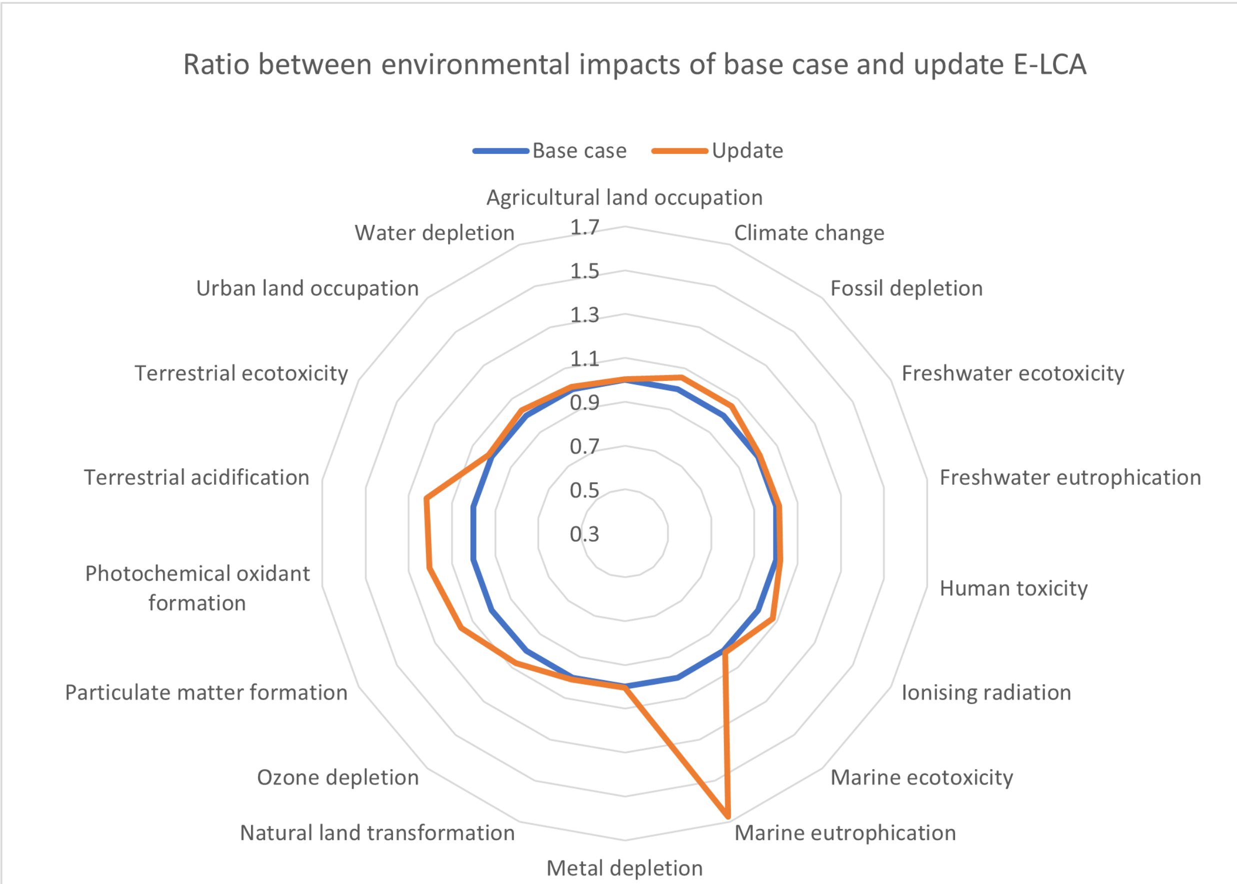


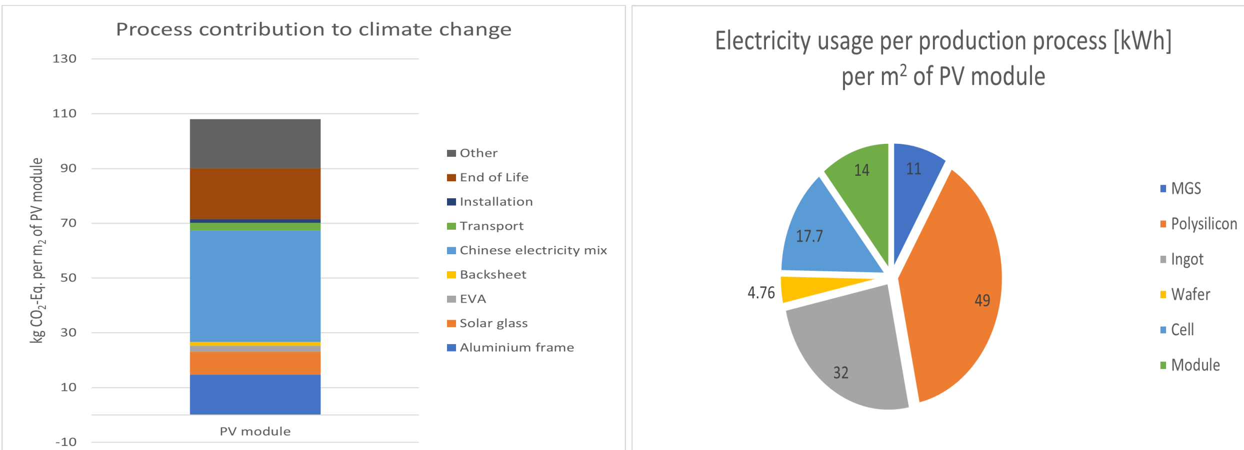
Figure 6.1: Ratio between environmental imapcts of base case and update E-LCA

Agricultural land occupation

All life cycle stages account for up to 8.71 m_2/year, of which 4.0 m_2/year is used to manufacture the pallet and 1.06 m_2/year is related to the manufacturing of the PV cells. The land occupation of the pallet is primarily due to the wood needed to produce the pallet. For this reason, it is recommended to Ecorus to start exploring opportunities to extend the lifetime of its pallets (e.g, reusing/recycling).

Climate change

The updated PV module is responsible for 108 kg CO_2-Eq. Figure 6.2 indicates the contributions of the involved processes to climate change. This figure shows that a major part is due to the Chinese electricity mix, which contributes with 50.7 kg CO_2-Eq.. This relatively high value is mainly caused by the high share of coal-fired plants in the electricity mixes that results in more greenhouse gas emissions. Furthermore, Figure 6.2b demonstrates the high electrical demands for polysilicon and ingots production, resulting in emission-intensive phases within the life cycle of a PV module. Other remarkable processes that heavily contribute to climate change are End-of-Life management (18.7 kg CO_2-Eq.), aluminum frame production (14.7 kg CO_2-Eq.), and glass production (8.4 kg CO_2-Eq.). Compared to the base case, the updated E-LCA resulted in a higher environmental impact; the adoption of coal-fired electricity during the MGS and polysilicon production and the addition of the transport (+ 2.79 kg) and installation (1.29 kg) phases result in an increase of 5% for this impact category. In conclusion, within the life cycle of a PV module, the most effective measures would be to make the polysilicon and ingot processes more efficient or to incorporate more renewables into the electricity mix.



(a) Process contribution to climate change

(b) Electricity usage per production process

Figure 6.2: E-LCA results - Climate change

Fossil depletion

This impact category and accounts for 27.8 kg oil-Eq for the entire life cycle of a PV module. Figure 6.3 shows that the biggest process contributors are the Chinese electricity mix (8.8 kg oil-Eq.), the aluminum frame (3.82 kg oil-Eq.), the solar glass (2.54 kg oil-Eq.), End of Life (2.14 kg oil-Eq.), and the EVA layer (1.73 kg oil-Eq.). Also, this impact category is increased with 2 kg oil-Eq. compared to the base case. Besides the updated energy mix, the machinery involved during installation, and transportation (freight ships and trucks) all operate on diesel. In summary, fossil depletion is heavily influenced by the electricity mix, implying that adopting more green energy to the electricity mix can reduce this impact category.

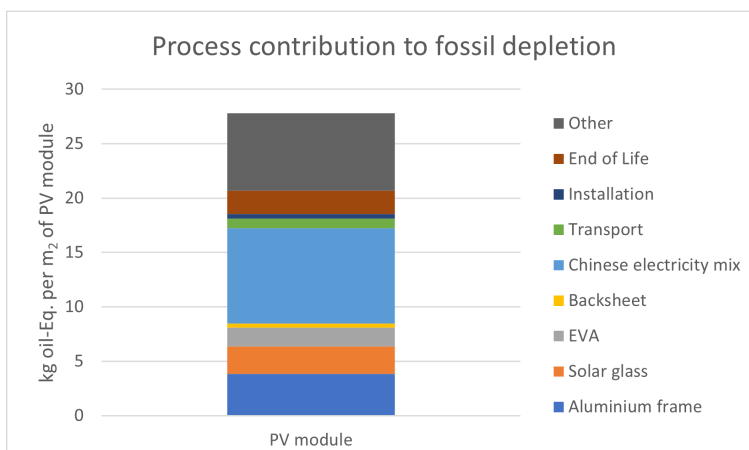


Figure 6.3: Process contribution to fossil depletion

Freshwater ecotoxicity

The value for this category equals 8.13 kg 1.4-DCB-Eq and the differences compared with the base case (0.0759 kg DCB-Eq.) are negligible. The biggest contributors to this category are the aluminum frame production (59%) and the metallization paste (used to increase panel performance) for the PV cell (14%). The most effective measure to address this impact would be to decrease the needed aluminium or by replacing this relatively heavy material with a suitable alternative (e.g., polymers).

Freshwater eutrophication

The impact of the PV module for this category is 0.0267 kg P-Eq. The Chinese electricity mix and the aluminium frame contribute both with 23%, while the metallization paste has an impact of 13% for this category. Besides the previously mentioned measures (adoption of renewables in electricity mix and lowering the weight of alumnium frame), also the consideration of a more environmentally friendly metallization paste could be beneficial for lowering this impact [55].

Human toxicity

The human toxicity category equals 37 1.4 DCB-Eq. The biggest contributors are (1) End of Life (18%), aluminium frame (17%), electricity mix (10%), and metallization paste (5%). Making the EoL phase more effective or lowering the amount of aluminum needed can lessen this impact. Related to the aluminium production, there is an involved residual salty oxide product, known as salt slag or salt cake. This salt slag is regarded as a hazardous and toxic waste [56].

Ionizing radiation

This category equals 6.6 kg U235-Eq. The End-of-Life (1.27 kg), aluminium frame production (1.2 kg), and the Chinese electricity mix (0.717 kg) are the three factors that contribute most to this impact category. These relatively high shares are mainly caused by the used electricity mix used in China and End-of-Life (assumed that this occurs in Europe), which rely on nuclear power. To decrease this environmental impact, the most efficient measure would be to decrease the share of nuclear power in the electricity mixes.

Marine ecotoxicity

For this impact category, there are no notable variations compared to the base case, and the result is 7.42 kg 1.4-DCB-Eq. A sizable 56% of this impact comes from the production of the aluminum, and 16% comes from the metallization paste. This impact category can be reduced by lowering the required aluminium or by applying a more environmentally friendly metallization paste. One of the gaseous pollutants from the manufacturing of aluminum is what is known as polycyclic aromatic hydrocarbons (PAH). These are carbon and hydrogen-based chemicals. Many of them are harmful to aquatic organisms (present in marine ecosystems) even at low exposure levels due to incomplete combustion [56].

Marine eutrophication

The environmental impact for this category is equal to 0.00664 kg N-Eq. Although the treatment of waste water during the cell and module production has a positive environmental impact (0.00325 kg), the negative impacts of the other processes outweigh the positive impact. Especially treatment of waste plastic during EoL accounts considerably with 0.00746 N-Eq., as well as the transport of the PV modules to the Netherlands (0.00211 kg). Compared to the base case, this impact category is increased with 68%. This is majorly caused by the addition of the transport (0.00211 kg N-Eq.) and installation (0.00314 kg N-Eq.). Generally, diesel engines emit NO and NO_2, which are known as NO_x. The impact of the marine eutrophication can be reduced by developing a more efficient technology for treating the waste plastic during EoL. Additionally, this impact can also be reduced by using a more environmentally friendly transportation (e.g., hydrogen-based freight transport).

Metal depletion

For the PV module, 36 kg of iron (Fe) is required (same as the base case). The main contributors are:

1. The required tin for soldering the electronic connections (79%)
2. The metallization paste, for improving the module performances (5 %)
3. And solar glass production (4%)

The most effective measure to reduce metal depletion would be to scale down the tin needed for the PV module. However, currently, the majority of the existing and price-competitive PV technologies rely on tin-based connections, meaning that alternatives are unfeasible for the time being.

Natural land transformation

The value for this impact category is negative (-0.0134), implying that the PV module has a positive environmental impact. For now, it remains unclear what caused this value.

Ozone depletion

The PV module has an impact of 9,7E^{-6} CFC-11-Eq, which is an 8% increase compared to the base case. The main contributors are: (1) backsheet production (38%); (2) End-of-Life (10%); (3) aluminium frame production (10%); (4) solar glass production; and (5) transport (5%). Making the backsheet more environmentally friendly would the most effective measure to address this impact category.

Particulate matter formation

The environmental impact category represents a value of 0.245 kg PM10-Eq. The most particulate matter is released during electricity production, in particular, in coal-fired plants (40%). Other notable processes are: the aluminium frame production (16%), solar glass production (9%), transport (9%), and EoL (5%). Compared to the base case, this impact category increased by 16%, mainly caused by the adoption of more coal-fired plants during the MGS and polysilicon production. Increased use of renewable energy sources in the electricity mix would significantly lessen this impact.

Photochemical oxidant formation

The total impact of this category accounts for 0.439 kg NMVOC-Eq., which is primarily attributable to China's coal-fired electricity (29%). Also the production of aluminium frames (12%) and transportation (12%) have a substantial contribution to this impact category. The photochemical oxidant formation is increased with 21.6% compared to the base case, which can mainly be attributed to the updating of the Chinese electricity mix. The higher share of coal-fired electricity results in more photochemical oxidant formation, implying that the integration of more renewables can reduce this impact.

Terrestrial acidification

One square meter of a PV module accounts for 0.539 kg SO_2-Eq. From this total impact, the Chinese electricity mix (37%), solar glass (13%), aluminium frame (13%), transport (12%), and recycling (4%) contribute most. Compared to the base case, this impact category for the updated

E-LCA is increased by 21.8%. It turns out that the update of the Chinese electricity mix is mainly responsible for this increase, apparent from a contribution of 0.199 kg SO_2 for the updated E-LCA, in contrast to a minor contribution of 0.0988 kg SO_2 for the base case.

Terrestrial ecotoxicity

The PV module accounts for 0.028 kg 1.4-DCB-Eq. The main contributor for this category is the required soap which accounts for 28%. The complex mixes of persistent and harmful active chemicals included in the soap can have negative effects on the environment. Additionally, the production of the corrugated board box and EVA production accounts for 25% and 8%, respectively. The most effective measure would be to encourage eco-friendly substitutions for the soap and corrugated board box.

Urban land occupation

The updated E-LCA results in the occupation of 1.18 square meters of urban land per year. The majority of this can be related to the Chinese coal-fired plants which take up 0.28 m_2/year of urban area. Additionally, the factory construction occupies 0.19 m_2 annually. Other processes that contribute are aluminium production (11%) and EoL (17%). Alternatives that require less urban land may be difficult to implement. Making solar panels more efficient is one step that could lower urban land occupation since by realizing this, the effective land occupation per panel for factory construction also decreases.

Water depletion

One square meter of a PV module accounts for 0.82 m_3 water-Eq. The silicon hydrochlorination, which accounts for 27% of the total water depletion is the main contributor. The aluminium production (12%), Chinese electricity usage (11%), and the manufacturing of solar glass (6%) are other impactful processes. Coal-fired electricity requires relatively high volume of water compared to other traditional electricity technologies. Generally speaking, making processes more efficient (in terms of water usage) is what should be pursued in technology developments.

6.1.1 Sensitivity analysis

Two different sensitivity analyses were executed: (1) one that analyses the results of a changing Chinese electricity mix; and (2) one that examines the influence of different ReCiPe perspectives.

First, the influence of different energy mixes on the E-LCA results will be analyzed. As mentioned in Chapter 6.1, it can be concluded that the electricity mix heavily contributes to the impact categories, which highlights the potential of integrating renewables. Therefore, an analysis is executed to investigate the environmental impact when adopting the Chinese electricity mix outlook for 2035 and 2050 which is visualized in Figure 6.4. This figure shows that, if the outlooks become true and with a few exceptions, most of the environmental impacts of solar panels will considerably be reduced in the upcoming decades because of the integration of renewables. Exceptions of these environmental reductions are impact cateogires *freshwater ecotoxicity*, *human toxicity*, *ionising radiation*, *marine ecotoxicity*, *ozone depletion*, and *terrestrial ecotoxicity*. It is anticipated that the significant contribution of wind energy in the energy outlook for 2035 (39%) and 2050 (49%) will be responsible for the rise in the toxicity effect categories. This is consistent with the argument made by Laurent et al. (2012) that switching from a fossil fuel-based European mix to wind power significantly reduces carbon footprint but may leave the toxicity impacts at the same or even higher levels [57].

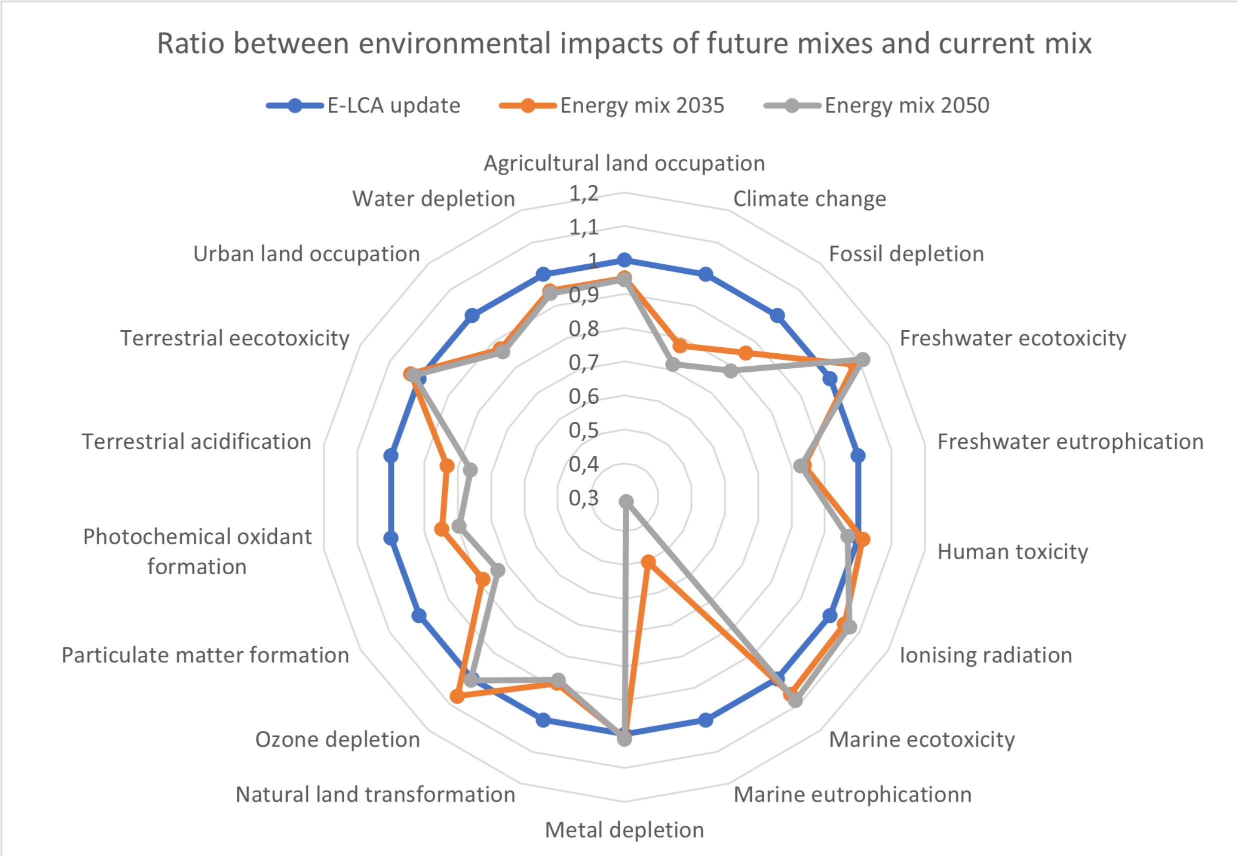


Figure 6.4: Sensitivity analysis 1: impact of different energy mixes on E-LCA results

Second, the impact of adopting a different worldview on the E-LCA results was examined. As mentioned in Chapter 3.4.1, three different world views can be recognized in the ReCiPe impact assessment method and these are adopted in the sensitivity analyses: (1) individualist; (2) hierarchist, and (3) egalitarian. Figure 6.5 shows the sensitivity analysis when adopting the individualist and Egalitarian world views in comparison with the E-LCA update (where the Hierarchist worldview is adopted). This figure shows that the E-LCA results are sensitive to different world views. When adopting an individual worldview, the *climate change* impact category increases by approximately 16%, while the *human toxicity*, *ionizing radiation*, and *marine ecotoxicity* decreases significantly with, 92%, 38%, and 53%, respectively. When adopting the egalitarian worldview, most impact categories are relatively robust; however, the *marine ecotoxicity*, *human toxicity*, and *terrestrial ecotoxicity* categories increase radically with a factor 462, 48, and 4.3. These massive factors suggest that the E-LCA results are not completely robust in terms of sensitivity. For the time being, the reason for this remains unclear so this might pose a possibility for future research

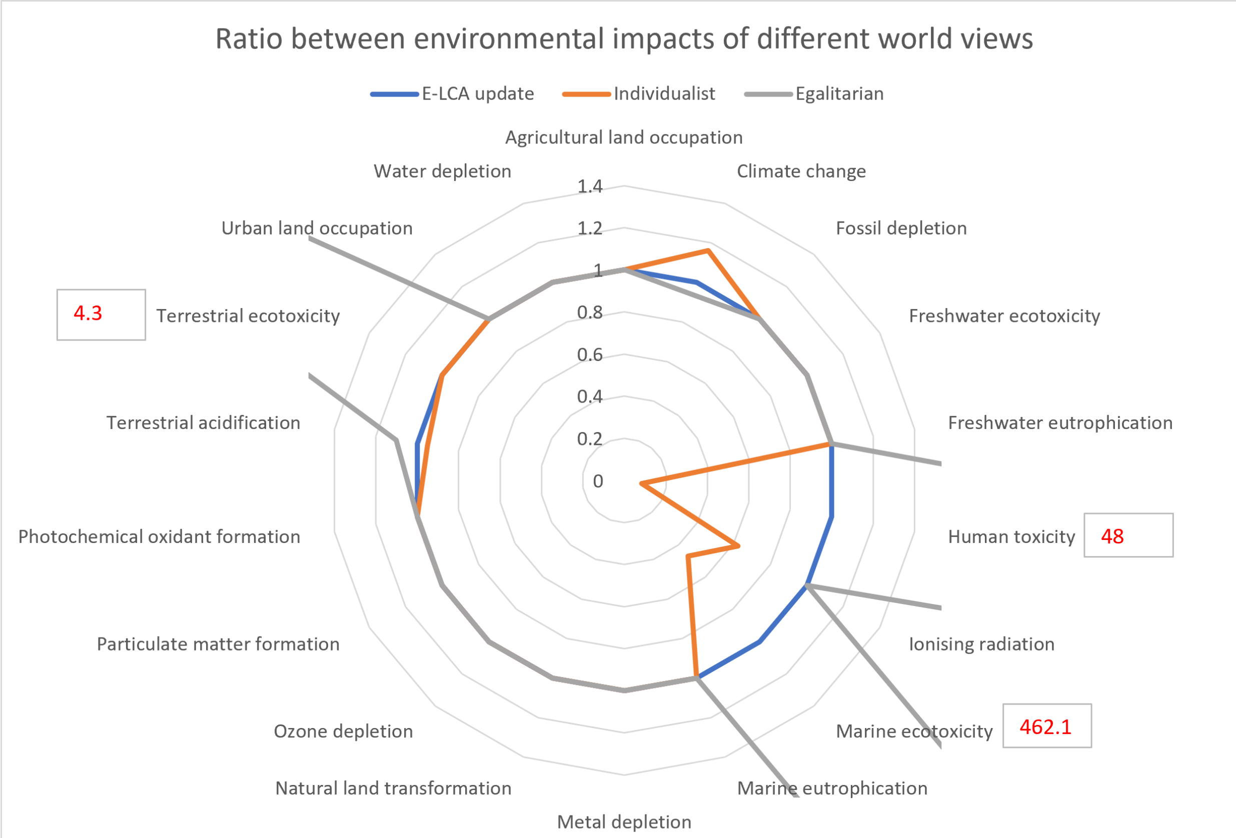


Figure 6.5: Sensitivity analysis 2: impact of different world views on E-LCA results

6.2 Interpretation

The research was conducted in order to update the environmental impacts and to realize a first assessment to identify potential social impacts of a PV module. Based on these identifications, it was intended to identify the environmental and social hotspots within the life cycle of a PV module.

Regarding the updating of the E-LCA, it can be concluded that especially the following impact categories are predominantly affected compared to the base case: *Marine eutrophication*, *Particulate matter formation*, *Photochemical oxidant formation*, and *Terrestrial acidification*. The main reason for this is because of the increased share coal fired electricity during the MGS and polysilicon production. This illustrates the added value of this study. Moreover, the results revealed that by updating the assessment, 8 out of the 18 impact categories were affected with more than 5% compared to the base case.

For the purpose of identifying the environmental hotspots, it can be concluded that within the considered system boundaries the main hotspots are located during the polysilicon and ingot production. The environmental life cycle assessment showed that the majority of the impact categories were significantly influenced by the Chinese electricity mix (8 out of the 18 categories). As can be seen in Figure 6.2, the most energy-intensive processes are the polysilicon and ingot production, implying that during these processes the majority of the interventions of emissions and resource uses will take place. Furthermore, other noteworthy hotspots with a smaller degree are the aluminium frame production (11 out of 18 categories are significantly influenced by the aluminium production) and End of Life (contributed considerably to four categories), which also both contribute considerably to the overall impacts.

Based on the sensitivity analyses, two conclusions can be drawn: (1) generally speaking, the environmental impacts of the PV module will decrease if the energy outlook become reality; and (2) the E-LCA are not completely robust if a different ReCiPe perspective is applied. This means that it is worth finding out the exact reason for this relatively high discrepancy in order to realize robust results.

Chapter 7

Discussion and Conclusion

To improve environmental and social performances, this study conducted a social- and environmental life cycle assessment (LCA) for an sc-Si PV module. The previous chapters covered the research topics and presented the main findings of the analyses that were conducted. In order to respond to the main research question, this chapter summarizes the key findings. Furthermore, this chapter also presents the limitations, implications, and possibilities for future studies are presented.

7.1 Key findings

The objective of this research was to identify social and environmental impacts that are related to the supply chain of an sc-Si PV module. To be specific, the research question this study aimed to answer was: *What are the environmental and social impacts of a typical Photovoltaics module?*

This research started with identifying a typical solar photovoltaic supply chain and has demonstrated that a typically imported PV module from China contains solar components originating from Xinjiang. A typical solar PV module supply chain consists of the following six stages: (1) extracting high-grade quartz; (2) melting this quartz into metallurgical-grade silicon (MGS); (3) refining the MGS into polysilicon; (4) purifying the polysilicon into mono-grade ingots; (5) converting the ingots into thin wafers; (6) Converting the wafers into cells; and (7) interconnecting the cells and sandwiching the whole between glass and plastic sheets. Although the considered PV module supplier, JA Solar, cannot be directly linked to Xinjiang, the required materials downstream of the supply chain are produced and bought from companies located in this region. The findings support a growing body of research indicating that the majority of the MGS and polysilicon production take place in Xinjiang, which is subsequently sold to JA Solar. In contrast with the MGS and polysilicon production which mostly takes place in one dominant province, the ingot, wafer, cell, and module production are more distributed across China. Yet, the results revealed that these processes mainly take place in the Eastern provinces due to easier access to global shipping and proximity to Chinese citizens. Furthermore, the PV module supply chain identification has also demonstrated that the MGS and polysilicon production plants heavily rely on cheap coal-fired electricity, which in turn could lead to higher environmental impacts.

The supply chain identification was evaluated on social and environmental performances using an S-LCA and E-LCA, respectively. The S-LCA has shown that the main social hotspots are located during MGS and polysilicon production. Given that the majority of the MGS and polysilicon production take place in the Xinjiang region, companies (e.g., JA Solar) downstream in the supply chain run significant risks of having their supply chain impacted by Xinjiang forced labor. Indigenous people from the Xinjiang region that are employed for these labor programs imply clear indicators of human trafficking and forced labor.

Moreover, the E-LCA revealed that by updating the assessment, 8 out of the 18 considered impact categories were affected by more than 5% compared to the base case. Furthermore, it can be concluded that within the considered system boundaries the main hotspots are located during the polysilicon and ingot production. The E-LCA has shown that the Chinese electricity mix strongly contributed to the bulk of the impact categories. Notably, the manufacturing of polysilicon and ingots are the most energy intensive processes, indicating that the majority of emissions and interventions will occur during these processes. Other noteworthy hotspots with a smaller degree are the aluminium frame production and End of Life, which also both contribute considerably to the impacts.

7.2 Limitations of the study

Several limitations of the study were identified that lowered the quality of the research. First, there is considerable controversy surrounding the gathered life cycle inventory for the S-LCA. The ingot, wafer, cell, and module worker were represented by sending a questionnaire to JA Solar and by using the sustainability report. However, the reliability of the provided answers to these questions can be questioned. This concern was covered during interviews with Hollandsolar and the Dutch embassy in Beijing. Both parties argued that little value should be attached to the outcomes of this questionnaire. This is mainly because these companies want to avoid that a bad image associated with them, but it also appears that the Chinese government is checking these questionnaires.

Second, there might be a moderate level of representativeness for the Chinese stakeholder group (except from the worker during MGS and polysilicon production). The indicators would ideally be measured by directly interviewing the involved stakeholders. Although this was done to represent the worker during installation, this wasn't realized to represent the Chinese worker due to resource limitations. This might lead to unreliable outcomes, and makes it unfeasible to conclude on the risk of social impacts for these stakeholder groups.

Third, there is some concern, generally speaking, about the fact that only a limited amount of indicators is used to represent a stakeholder group. Since this is a high-level study, there is a risk of drawing conclusions too quickly. As this study was a first attempt to assess the social impacts it is not inconceivable that all stakeholder group are only represented in a low level of detail. Therefore, it was chosen to focus on the worker stakeholder group and pay less attention to the remaining groups. It is plausible that a number of limitations could arise from this; for example, it might be that there are social impacts being overlooked for the stakeholder groups with less focus.

Fourth, the major limitation in the used impact assessment method is the simplified weighing scheme that is applied. This research converts all indicators values for each stakeholder group into value to summarize a stakeholder group by arithmetic averaging. This strategy suggests that each impact category and indicators are equally important. However, it is possible that some indicators differ in importance or concerning phenomena that should be highlighted more than others. This research neglects this feature.

The last limitation is that the majority of the inventory data for the E-LCA is based on background data which is sometimes outdated. This outdated data can result in a lower level of representativeness of the study compared to reality. Although the energy mix is updated in this research, there might be other processes that should ideally also be updated to better represent the actual environmental impacts.

7.3 Implications of the study

Despite being a renewable energy source, solar panels can nevertheless have an impact on the environment and/or humans. Given the growing interest in these disciplines, it is crucial to carefully consider how a PV module may affect those fields. The environmental and social assessment of a PV module allows for identifying stages within the life cycle that have the most impact (hotspots). For this purpose, this study performs an Environmental- and Social Life Cycle Assessment (LCA) for a typical PV module. This chapter discusses the implications of the study.

For the scientific purpose, this study's objective is to establish the first identification of a PV module's social implications and to update the environmental impacts. This study executes a quantitative analysis of the environmental impacts of a solar panel from a life cycle perspective. This study shows that updated E-LCA has a worse environmental profile compared to the base case study (which uses the most recent inventory data by). By updating the E-LCA, 8 out of the 18 considered impact categories were affected by more than 5% compared to the base case

For the LCA community, since this is the first social life cycle assessment conducted of a PV module, this study serves as the first assessment of its social performance. This study aims to provide insights in order to improve environmental and social performances. Based on the outcomes of the study, potential improvements on different levels are suggested. Next chapter discusses these possibilities in more detail.

7.4 Possibilities for future research

The first recommendation for future studies suggest to realize a more detailed follow-up S-LCA. This research prioritized in the S-LCA by focusing on the worker stakeholder group and putting less effort to the other stakeholder groups. Therefore, it is recommended to realize a more detailed follow-up study that includes more indicators for the local community, society, consumers, and children stakeholder groups. This research follows a top-down approach since the impact categories and indicators are selected based on incorporating the recommendations of the United nations. Future studies might find value to follow a mixed-method approach (top-down and bottom-up); for example, by including indicators that are important to the stakeholder groups in question (e.g., the importance of human rights for the company according to its employees). Preferably all indicators are measured with primary data by directly interviewing stakeholders. However, practical difficulties could arise when it is intended to engage with potentially affected stakeholders.

Second, this research recommends to implement a weighting mechanism during the social life cycle impact assessment. This research converts all indicator values for each stakeholder group into one value by arithmetic averaging. This method implies that an equal weight in assigned to every indicator; however it might be that specific indicators represent crucial or alarming phenomena that should be more emphasized than other indicators. Therefore a weighing mechanism would provide opportunities to give more importance to those indicators that are most critical or that are most aligned with the goal of the S-LCA. In addition, a more detailed weighting scheme is also recommended for calculating the representativeness score for the inventory data. This research calculates this score by using arithmetic averaging, meaning that any bad value of one category can be compensated by a good value of another category. Now it seems that some inventory meets the data quality requirements, while the data is totally based on subjective grounds. It could be beneficial to design a scoring system that disqualifies inventory data if any of the data quality categories is excessively high.

Third, it is also worth studying the environmental impacts when incorporating the applied energy mixes which are present during all involved processes by directly requesting this to the involved companies. This research assumes the average Chinese electricity mix for the ingot, wafer, cell, and module production, while it might be that the actual mixes differ from this average mix used in the E-LCA. When identifying the exact location of all factories for these processes, the electricity mix can be applied in the E-LCA that is present in this specific region. It might be that some factories are located in Chinese provinces which predominantly use hydropower instead of the average Chinese electricity grid. By incorporating these actual mixes, this allows to represent reality more accurately.

Last, it is proposed that further research should be undertaken in the field of hotspot analysis. One of the intended application of this research was to identify the environmental hotspots within the considered system boundary. For this purpose, the extent of recurrence was considered as main driver for concluding on the environmental hotspot. This has shown that the Chinese electricity mix often contributes to the environmental impact categories. To conclude on the robustness of the E-LCA results, future studies should concentrate on other hotspot analysis methods. For example, the Life Cycle Initiative is working on an emerging approach to identify environmental hotspots. It worth studying how the various calculated hotspots look like when applying different hotspot analysis methods.

7.5 Recommendations for Ecorus

Given that a draft legislation was submitted to the European Commission to require mandatory supply chain due diligence for all companies that sell products and services within the European Union, denotes the importance of continuing with CSR. Therefore, based on the outcomes of the research recommendations were suggested to Ecorus in the field of CSR.

The results revealed that the environmental hotspot of a PV module is located during the polysilicon and ingot production, which are mainly contributed by the Chinese electricity mix. Although Ecorus cannot exert any direct influence here, it is worthwhile entering into a conversation with JA Solar to explore possibilities to make the energy mix more sustainable. With regard to the energy mix present during polysilicon production, it will be more difficult to enter into a direct dialogue with, for example, Daqo. That is why there may be opportunities to select only suppliers who use green energy mixes. For example, Tongwei, a Chinese polysilicon producer that has been committed to establishing a vertically integrated PV supply chain in recent years. From an environmental perspective, this is promising given that they aim to set up this supply chain in the Sichuan province, which mainly uses hydro-based electricity. This will therefore result in fewer environmental impacts.

Furthermore, to further reduce environmental impacts, it is suggested to stay informed about innovative technologies. For instance, extensive research is now being conducted to increase module efficiency by utilizing Perovskite solar cells. Although this type of solar cell has not been commercialized yet, the fact that this type of solar cell can theoretically reach efficiencies of 27.4% denotes its potential [58]. In addition, exploring opportunities to reduce panel weight (e.g., by using plastics instead of aluminium frames) might also be beneficial from an environmental perspective.

Although most of the environmental impacts are caused during manufacturing, it is recommended to minimize impacts during Ecorus her own operations, which is the installation of a solar plant. The construction of a solar plant involves numerous machinery, all of which have an impact on the environment. For a ground project, the following types of machinery are frequently used: (1) forklift truck – for transporting materials; (2) ramming machine – for direct ramming of steel cross-section into the ground (to attach the panels); (3) excavator – for digging that allows for cable management; and (4) generator – for supplying the site (equipment) with its necessary energy.

These machines generally operate on diesel due to the high power demands. The diesel generator, however, is often equipped with a battery package in order to reduce the required fuel. Figure 7.1 shows the percentual change in environmental impact for different installation scenarios compared to the case where the diesel generator is equipped with a battery pack. This figure shows that the environmental impacts are significantly increased if the battery pack is excluded; however, it also shows the potential of powering the site with a grid connection. This latter can be obtained by timely requesting a grid connection to the grid operator. Therefore it is suggested to adopt this in future project management. There are currently few alternatives to renting electricity-powered machines machinery since high power is required for the working activities. However, it is recommended to remain in close contact with the rental companies to stay updated on any innovative green alternatives.

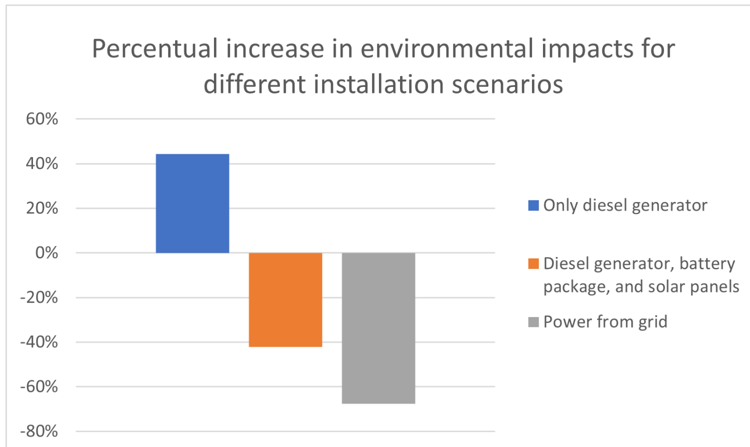


Figure 7.1: Percentual change in environmental impacts for different installation scenarios

Moreover, the results of the S-LCA also showed that the main hotspots are located during the MGS and polysilicon production. It is expected that it will be difficult for Ecorus to solve this problem. Therefore, it is recommended to intensify the relationship with HollandSolar (the Dutch trade association for all companies active in the solar sector). Subsequently, joint discussions with other solar developers can take place that leads to broad agreement on best practices for sustainable procurement. In the long term, this could perhaps lead to a sector initiative at European level that can exert more pressure to improve social conditions in the Xinjiang region.

Furthermore, as discussed earlier, Tongwei is establishing a vertically integrated supply chain in the Sichuan province. This implies that no labor programs are involved which leads to better social performance. Therefore, it is suggested to start exploring whether a relationship can be realized with Tongwei. Last, it is recommended to carefully track the work hours of the workers during installation. Currently, it seems that these hours are close to the maximum amount allowed.

Bibliography

[1] International Energy Agency Photovoltaic Power Systems Programme, "Snapshot of global pv markets - 2020." https://iea-pvps.org/snapshot-reports/snapshot-2020/https://iea-pvps.org/snapshot-reports/snapshot-2020/, 2020.

[2] Frischknecht, R.; Stolz, P.; Krebs, L.; de Wild Scholten, M.; Sinha, P., "Life cycle inventories and life cycle assessments of photovoltaic systems 2020 task 12 pv sustainability." https://iea-pvps.org/, 2020.

[3] Hauschild, M.; Rosenbaum, R.; Olsen, S., "Life cycle assessment." https://link.springer.com/book/10.1007/978-3-319-56475-3, 2018.

[4] Pedersen Weidema, B.; Suhr Wesnaes, M., "Data quality management for life cycle inventories-an example of using data quality indicators." https://www.sciencedirect.com/science/article/pii/S0959652696000431, 1996.

[5] Fraunhofer ISE, "Photovoltaics report." /www.ise.fraunhofer.de, 2022.

[6] Solar Energy Industries Association, "Solar supply chain traceability protocol 1.0." https://www.seia.org/research-resources/solar-supply-chain-traceability-protocol, 2021.

[7] U.S. Department of Energy, "Solar photovoltaics supply chain review report." https://www.energy.gov/eere/solar/solar-photovoltaics-supply-chain-review-report, 2022.

[8] Zhongying, W; Sandholt, K., "Thoughts on china's energy transition outlook." https://link.springer.com/article/10.1007/s41825-019-00014-w, 2019.

[9] Internatioanl Energy Agency, "Cross-border electricity trading for tajikistan: A roadmap." https://www.iea.org/reports/cross-border-electricity-trading-for-tajikistan-a-roadmap, 2021.

[10] International Energy Agency, "China." https://www.iea.org/countries/china, 2022.

[11] Bonilla-Alicea, R.; Fu, K., "Social life-cycle assessment (s-lca) of residential rooftop solar panels using challenge-derived framework." https://link.springer.com/article/10.1186/s13705-022-00332-w, 2022.

[12] United Nations Industrial Development Organization, "What is csr?." https://www.unido.org/our-focus/advancing-economic-competitiveness/competitive-trade-capacities-and-corporate-responsibility/corporate-social-responsibility-market-integration/what-csr, 2022.

[13] Müller, A.; Müller, A.; Reicehl, C.; Herceg, S.; Mittag, M.; Neuhaus, D., "A comparative life cycle assessment of silicon pv modules: Impact of module design, manufacturing location and

inventory." https://www.sciencedirect.com/science/article/pii/S0927024821003202?casa_token=knQM4hCztAgAAAAA:jJD7Tvrzv-svfJFUak6ISL_D1K_lvn-UsHx3mTS0Eu5P2z-G_Tk986ppZFOnlNHvkMsULb0mdQ, 2021.

[14] Norris, B.; Franze, B., "The methodological sheets for sub-categories in social life cycle assessment (s-lca)." https://www.lifecycleinitiative.org/library/methodological-sheets-for-subcategories-in-social-life-cycle-assessment-s-lca-2021/, 2023.

[15] Muteri, V.; Cullura, M; Curto, D.; Franzitta, V; Longo, S.; Mistretta, M; Parisi, M., "Review on life cycle assessment of solar photovoltaic panels." https://www.mdpi.com/1996-1073/13/1/252, 2020.

[16] Stamford, L.; Azapagic, A., "Environmental impacts of photovoltaics: The effects of technological improvements and transfer of manufacturing from europe to china." https://onlinelibrary.wiley.com/doi/full/10.1002/ente.201800037, 2018.

[17] Kabir, E.; Kim, K.; Szulejko, J., "Social impacts of solar home systems in rural areas: A case study in bangladesh." https://www.mdpi.com/1996-1073/10/10/1615, 2017.

[18] Traverso, M.; Asdrubali, F.; Francia, A; Finkbeiner, M., "Towards life cycle sustainability assessment: An implementation to photovoltaic modules." https://link.springer.com/article/10.1007/s11367-012-0433-8, 2012.

[19] Dubey, S.; Jadhav, N.; Zakirova, B., "Socio-economic and environmental impacts of silicon based photovoltaic (pv) technologies." https://www.sciencedirect.com/science/article/pii/S1876610213000830, 2013.

[20] Huang, B.; Zhao, J.; Chai, J.; Zhao, F.; Wang, X., "Economic and social impact assessment of china's multi-crystalline silicon photovoltaic modules production." https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12576?casa_token=taAPE6KSbAAAAAAA%3A7bMp4jLV78jCSFUBCHwJLd_ufgA7ithAjDDA3-hsR5x5QNxgANpCaAlDFUQpmRUc2r1qJtAeg_s0bnY, 2017.

[21] Ecoinvent, "Ecoinvent database v.3.7.." www.ecoinvent.org, 2022.

[22] Takeda, S.; Keeley, A.; Sakurai, S.; Managi, S.; Norris, B., "Are renewables as friendly to humans as to the environment?: A social life cycle assessment of renewable electricity." https://www.mdpi.com/2071-1050/11/5/1370, 2019.

[23] E. C. J. R. Centre.

[24] UNEP, SETAC, Life Cycle Initiative, "Social life cycle assessments of products." https://www.unep.org/resources/report/guidelines-social-life-cycle-assessment-products, 2022.

[25] Finnveden, G; Ekvall, M.; Guinee, T.; Heijungs, J.; Hellweg, R.; Koehler, S.; Suh, D, "Recent developments in lca." https://www.sciencedirect.com/science/article/pii/S0301479709002345?casa_token=HbL577a867kAAAAA:0d-D_TuPsw9dLEeFeh-9a0IafVElv4WqUluqPhdM9lnDiTBP8rXpoFLqt6NGD0TC0cmlz23z8g, 2009.

[26] Baliozian, P.; Tepner, S., "The international technology roadmap for photovoltaics and the significance of its decade-long projections." https://www.ise.fraunhofer.de/, 2020.

[27] Steubing, B.; de Koning, D.; Haas, A.; Mutel, C., "The activity browser — an open source lca software building on top of the brightway framework." https://www.sciencedirect.com/science/article/pii/S2665963819300120, 2020.

[28] Traverso, M.; Valdivia, S.; Luthin, A.; Roche, L.; Arcese, G.; Neugebauer, S.; Petti, L.; D'Eursanio, M.; Tragnone, B.; Mankaa, R., "Methodological sheets for subcategories in social life cycle assessment (s-lca) 2021." https://www.lifecycleinitiative.org/library/methodological-sheets-for-subcategories-in-social-life-cycle-assessment-s-lca-2021/, 2021.

[29] Stolz, P.; Frischknecht, R., "Life cycle assessment of current photovoltaic module recycling." https://iea-pvps.org/key-topics/life-cycle-assesment-of-current-photovoltaic-module-recycling-by-task-12-2/, 2017.

[30] Freeman, R., "Strategic management: a stakeholder approach." https://onlinelibrary.wiley.com/doi/abs/10.1111/b.9780631218616.2006.00007.x, 1984.

[31] Murphy, L.; Elimä, N., "In broad daylight: Uyghur forced labour and global solar supply chains." https://www.shu.ac.uk/helena-kennedy-centre-international-justice/research-and-projects/all-projects/in-broad-daylight, 2021.

[32] United Nations Human Rights, "Ohchr assessment of human rights concerns in the xinjiang uyghur autonomous region, people's republic of china." https://www.ohchr.org/en/documents/country-reports/ohchr-assessment-human-rights-concerns-xinjiang-uyghur-autonomous-region, 2022.

[33] JA Solar, "Sustainability report in 2021." http://www.jasolar.com./, 2021.

[34] Greenchoice, "Greenchoice geïntegreerd jaarverslag." https://jaarverslag.greenchoice.nl/, 2022.

[35] Pre Sustainability, "Recipe." https://pre-sustainability.com/articles/recipe/, 2021.

[36] Investopedia, "Sensitivity analysis definition." https://www.investopedia.com/terms/s/sensitivityanalysis, 2022.

[37] Bernreuter Research, "Polysilicon uses." https://www.bernreuter.com/, 2022.

[38] Hoshine Silicon Industry, "Corporate culture." http://www.hoshinesilicon.com, 2022.

[39] Daqo New Energy, "Esg 2021 environmental, social, and governance report." http://ir.xjdqsolar.com/index.php?s=/Index/annual, 2021.

[40] Business Human Rights Resource Centre, "China solar panel factory shut after protests." https://www.business-humanrights.org/en/latest-news/china-solar-panel-factory-shut-after-protests/, 2022.

[41] HollandSolar, "Vragen over oeigoerse dwangarbeid in de keten van zonnepanelen." https://hollandsolar.nl/veelgesteldevragen/vragen-over-oeigoerse-dwangarbeid-in-de-keten-van-zonnepanelen, 2022.

[42] International Labour Organization, "Ilo indicators of forced labour." https://www.ilo.org/global/topics/forced-labour/publications/WCMS_203832/lang--en/index.htm, 2022.

[43] PV Magazine, "Solar panel recycling in the us — a looming issue that could harm industry growth and reputation." https://pv-magazine-usa.com/2020/12/03/solar-panel-recycling-in-the-us-a-looming-issue-that-could-harm-growth-and-reputation/, 2020.

[44] RatedPower, "Rare metals in the photovoltaic industry." ://ratedpower.com/blog/rare-metals-photovoltaic, 2022.

[45] International Energy Agency, "Solar pv global supply chains." https://www.iea.org/reports/solar-pv-global-supply-chains, 2022.

[46] Hepburn, C; Qi, Y.; Stern, N; Ward, B; Xie, C; Zenghelis, D., "Towards carbon neutrality and china's 14th five-year plan: Clean energy transition, sustainable urban development, and investment priorities." https://www.sciencedirect.com/science/article/pii/S2666498421000545, 2021.

[47] EJAtlas, "Antipollution protests against solar panel manufacturers, quanzhou, fujian, china." https://ejatlas.org/conflict/antipollution-protests-against-local-solar-panel-manufacturers-quanzhou-fujian-china, 2021.

[48] Transparancy International, "Corruption perceptions index china." https://www.transparency.org/en/cpi/2021/index/chn, 2022.

[49] PV Magazine, "Ja solar chairman detained by anti-corruption authorities in china." https://www.pv-magazine.com/2020/11/11/ja-solar-chairman-detained-by-anti-corruption-authorities-in-china/, 2021.

[50] Unicef, "Education." https://www.unicef.cn/en/what-we-do/education, 2021.

[51] Greenchoice, "Klantenservice." https://www.greenchoice.nl/klantenservice/, 2022.

[52] Tweakers, "Datalek bij greenchoice." https://gathering.tweakers.net/forum/list_messages/2078622, 2022.

[53] European WEEE Directive, "Collection recycling." http://www.solarwaste.eu/collection-and-recycling/, 2022.

[54] Rijksoverheid, "Energiecontract voor elektriciteit." https://www.rijksoverheid.nl/wetten-en-regelingen/productbeschrijvingen/energiecontract-voor-elektriciteit#:~:text=In%20Nederland%20heeft%20u%20de,uw%20energierekening%20niet%20kunt%20betalen., 2021.

[55] Quande, C; Hongxing, Y.; Yuanhao, W., "A new environmental friendly silver front contact paste for crystalline silicon solar cells." https://www.researchgate.net/publication/257361482_A_new_environmental_friendly_silver_front_contact_paste_for_crystalline_silicon_solar_cells, 2021.

[56] Brough, D.; Jouhara, H., "The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery." https://www.sciencedirect.com/science/article/pii/S2666202719300072, 2020.

[57] Laurent, A.;, Olsen, S.; Hauschild, M., "Limitations of carbon footprint as indicator of environmental sustainability." https://pubs.acs.org/doi/full/10.1021/es204163f, 2012.

[58] PV Magazine, "All perovskite tandem solar cell with 27.4% efficiency, high voltage." https://www.pv-magazine.com/2022/11/17/all-perovskite-tandem-solar-cell-with-27-4-efficiency-high-voltage/, 2022.

Appendix

Electricity mixes

	Unit		Below 2		
		2017	2020	2035	2050
Total power generation capacity	GW	1746	2108	5366	6814
Renewable	GW	621	842	4362	6159
Hydro	GW	313	343	454	532
Wind	GW	163	221	1826	2664
Bio (solid, liquid, gaseous)	GW	15	48	64	57
Solar	GW	130	224	1962	2803
Solar CSP	GW	0	5	38	33
Geothermal	GW	0	1	5	20
Ocean	GW	–	0	13	50
Nuclear	GW	36	58	96	120
Fossil fuels	GW	1088	1208	907	536
Total electricity generation	TWh	6313	7859	13,324	15,324
Renewable	TWh	1676	2186	9545	13,488
Hydro	TWh	1153	1249	1622	1831
Wind	TWh	328	496	5 159	7 612
Bio (solid, liquid, gaseous)	TWh	44	146	221	268
Solar	TWh	151	277	2380	3439
Solar CSP	TWh	0	14	100	86
Geothermal	TWh	0	4	38	153
Ocean	TWh	–	0	26	100
Nuclear	TWh	257	442	735	915
Fossil fuels	TWh	4381	5231	3044	920

Figure 7.2: Chinese Installed power generation capacity and total electricity generation for the below 2 Â°C scenario in 2017, 2020, 2035, and 2050 (taken from Zhongying and Sandholt (2019) [8])

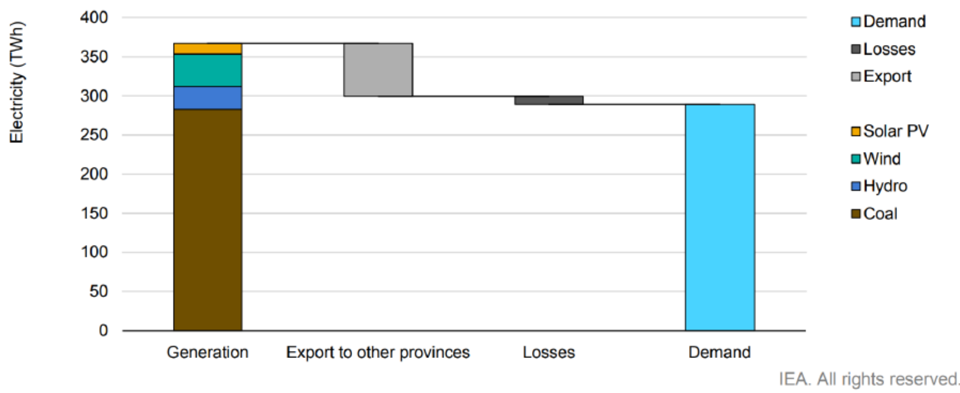


Figure 7.3: Power generation, export, and electricity demand in Xinjiang province in 2019 (taken from IEA (2021) [9])

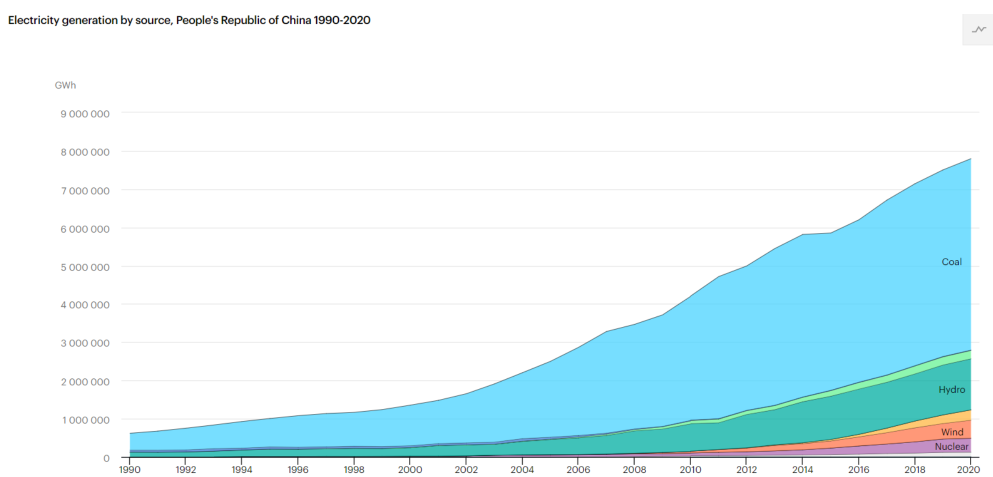


Figure 7.4: Electricity generation by source of China (taken from IEA website (2022) [10])

Indicator Selection

Table 7.1: List of selected indicators for worker stakeholder group

#	Indicator	Impact category	Desired direction/ answer
1	Right of workers to join organizations of their choosing	Freedom of association and collective bargaining	Yes
2	Employment is not conditioned by any restrictions on the right to collective bargaining		No
3	Presence of child labor	Child labor	No
4	Presence of unpaid labor	Fair salary	No
5	Involvement of known and regular payment		Yes
6	Presence of unclear wage deductions		No
7	Employees are paid at least by the legally mandated minimum wage		Yes
8	Compliance with legal rules for working hours	Working hours	Yes
9	Compliance with legal rules for pause periods		Yes
10	Compliance with legal rules for leave of absence	Social benefits/ social security	Yes
11	Employees are covered by health insurance		Yes
12	Employees are covered by retirement insurance		Yes
13	Presence of a formal policy concerning health and safety	Health and safety	Yes
14	Employees that can consistently use appropriate safety equipment		Yes
15	Employees getting training and educated if needed before starting with working activities		Yes
16	Presence of human rights lawsuits against the company		No
17	The organization has pledged to comply with the global compact principles and has engaged itself to present yearly		Yes
18	Presence of explicit code of conduct that protect human rights of workers among suppliers		Yes

Table 7.1 (continued)

#	Indicator	Impact category	Desired direction/ answer
19	Presence of abuse of vulnerability	Forced labor	No
20	Presence of deception		No
21	Restriction of movement		No
22	Isolation		No
23	Physical and sexual violence		No
24	Intimidation and threats		No
25	Retention of identity documents		No
26	Withholding of wages		No
27	Debt bondage		No
28	Abusive working and living conditions		No
29	Excessive overtime		No
30	Presence of formal policies on equal opportunities	Discrimination	Yes
31	Presence of formal policies on combating discrimination		Yes
32	Presence of any form discrimination incidents		No
33	Presence of a written contract that defines the relationship between the employer and workers (rights and responsibilities)	Employment relationship	Yes
34	Presence of sexual harassment incidents	Sexual harassment	No
35	Existence of clear responsibilities for matters of sexual harassment within the organization		Yes

Table 7.2: List of selected indicators for consumer stakeholder group

#	Indicator	Impact category	Desired direction/ answer
36	Availability of mechanism where consumers can provide feedback	Feedback Mechanism	Yes
37	Presence of internal management system to protect consumer privacy	Consumer Privacy	Yes
38	Presence of consumer complaints related to breach of privacy or loss of data within the last year		No
39	Presence of management measures to assess consumer health and safety	Health and safety	Yes
40	Presence of a quality and/or product safety management system such as ISO		Yes
41	Possibility of technology components to be reused or recycled for other purposes	End of Life responsibility	Yes
42	Presence and quality of infrastructure to responsibly dispose of product components		Yes
43	Presence of consumer complaints regarding transparancy	Transparency	No
44	Presence of public sustainability report		Yes
45	Electricity consumers have a choice in the utility company that will provide the technology		Yes

Table 7.3: List of selected indicators for local community stakeholder

#	Indicator	Impact category	Desired direction/ answer
47	Presence of individuals that have experienced involuntary relocating that can be attributed to the organization	Delocalization and Migration	No
48	Evidence of policies/management plan(s) in place to protect and/or support cultural heritage	Cultural Heritage	Yes
49	Presence of relevant organizational information to community members in their spoken language(s)		Yes
50	Presence of policy to protect the rights of indigenous community members	Respect of indigenous rights	Yes
51	Presence of documented illegal activities		No
52	Organization commitment to accept indigenous land rights		Yes
53	Number of legal complaints per year against the organization with regard to security concerns	Secure living conditions	No
54	Presence of policy to minimize hazardous substances	Safe & healthy living conditions	Yes
55	Presence of hazardous substances during product operation		No
56	Level of (rare) material resource use due to product design decisions	Access to material resources	No
57	Product or technology design makes use of local resources and expertise		Yes

Table 7.4: List of selected indicators for children stakeholder

#	Indicator	Impact category	Desired direction/ answer
69	Presence of stimulating measures to enhance education systems to communities	Education provided in the local community	Yes
70	Presence of equitable access to education		Yes
71	Formalized commitment of organization to improve the health of children	Health issues for children as consumers	No
72	The organization has a policy on responsible marketing	Children concerns regarding marketing practices	No

Table 7.5: List of selected indicators for society stakeholder

#	Indicator	Impact category	Desired direction/ answer
59	Presence of public agreement to sustainability using the selected technology	Public commitments to sustainability issues	Yes
60	Presence of protests to the proposed technology	Prevention & mitigation of armed conflicts	No
61	Partnerships in research and development	Technology development	Yes
62	Investments in research and development		Yes
63	Existence of technology efficiency improvement over years		Yes
64	Presence of revenue growth of the organization	Contribution to economic development	Yes
65	Formalized commitment of the organization to prevent corruption	Corruption	Yes
66	Acceptable level of corruption perception index		Yes
67	Involvement of company in corruption or other unethical practices		No
68	Formalized commitment of the organization to reduce poverty	Poverty alleviation	Yes

Example of interview with PV installer stakeholder

Interview with the representative of Future GmbH was conducted to identify social impacts when installing PV panels. Ecorus outsources the installation of solar panels to third parties. One of these parties is future GmbH, a company that specializes in installing electrical installations and solar plants. The interview lasted approximately 40 minutes and was conducted through a video conference on Teams on August 2, 2022.

Topic guide and questions

Introduction

First of all, thank you for reserving some time for allowing me for interviewing you. I appreciate this. I suggest that we begin with a brief introduction to get to know each other. So let me begin then. My name is Jan Roelofs, I am 23 years old and I study Sustainable Energy Technology at the technical university Eindhoven. I am doing my graduation project at Ecorus, which is a company that develops, builds, maintains, and finances solar power installations. The reason for contacting you is because I believe that you gain certain specific knowledge that may contribute to my research. This research is being conducted to identify the environmental and social impacts of Chinese PV modules. More concretely, I aim to assess the supply chain of Ecorus solar panels in terms of environmental and social performances. The assessment categories are in line with the sustainability principles of the United Nations. For this research, all different phases of the PV module are considered, including the PV installation. To evaluate the social impacts and benefits, I would like to utilize the experiences of persons that install the PV modules.

I am conducting this research for my master's thesis at the University of Eindhoven in the Netherlands. The questions I would like to ask you relate to the topics of human rights and labor conditions. Everything you tell me will only be used for this research project. Also, your name will not be used, to make sure that no one can identify you with any answers. Since I would like to use your answers for this research, I would like to record this conversation. Do you agree with this?

Do you have any questions before we begin?

Opening questions

1. *Could you please introduce yourself?*
2. *What kind of working activities are you carrying out?*
3. *For how long have you been working at Future?*

Key questions

1. *Could you explain what the recruitment process is looking like?*
2. *For how long are the employees working in the Netherlands on average?*
3. *Did the employees all join this organization of their choosing?*
4. *Are all employees able to negotiate about their contract?*
5. *Are the employees represented in a collective agreement?*
6. *Are you known for child labor within the company?*
7. *Have you experienced unpaid labor within the company?*
8. *Are all employees getting paid at known and regular intervals?*
9. *Are you familiar with deductions on wages of employees that were enacted for unclear reasons?*
10. *Is everybody being paid with the minimum required by law?*
11. *Is the wage transferred via a transaction to a bank?*
12. *Do the employees receive a clear payslip?*
13. *What is the average number of hours effectively worked by the employees?*
14. *How many days can the employees take a day off, according to their contract?*
15. *What is the average number of holidays that are used by employees?*
16. *Are all employees covered by health insurance?*
17. *Are all employees covered by retirement insurance?*
18. *Are there company-level safety certifications?*
19. *Do all employees have the required safety certifications?*
20. *Have you ever experienced hazardous working activities of employees (for example, working without adequate protective gear)?*
21. *In case hazardous working activities were reported, has the company taken appropriate measures to address this?*
22. *Is the appropriate safety equipment for workers' activities consistently available and accessible for all employees and are these being used anytime?*

23. *Were all employees appropriately trained and educated before starting with your working activities?*
24. *To what extent have the employees knowledge of the Dutch language?*
25. *To what extent have the employees knowledge about Dutch laws?*
26. *Did the company fix the housing for the employees?*
27. *How many housing options did the employees have when coming to the Netherlands?*
28. *Are you known for a mismatch between the promised working activities and the actual working activities?*
29. *Does the living conditions, wages, and amount of days off correspond to what was promised when the employees were hired for this company?*
30. *Are the employees completely free to enter and exit the work premises at any time?*
31. *Are the employees completely free to enter and exit your housing?*
32. *Have you experienced employees feeling isolated from the rest of the world?*
33. *Have you experienced physical and/or sexual violence among the employees?*
34. *Have you experienced situations where employees experienced violence that made them undertake tasks that were not part of the initial agreement?*
35. *Have you experienced intimidation and/or threats when employees complained about their working/living conditions? (for example, loss of wages, or no longer getting access to your housing)*
36. *Do the employees have access to their passports and other personal valuable possessions at any time?*
37. *Have you experienced that the wages of employees were withheld?*
38. *Have you experienced that employees ever worked in an attempt to pay off an incurred or inherited debt for the employer?*
39. *Are you known for differences in salary between men and women within the same function?*
40. *Are you known for differences in salary between your employees and Dutch employees who do the same working activities?*
41. *How satisfied are you with the company in terms of realizing appropriate working conditions?*
42. *How satisfied are you with the company in terms of ensuring appropriate living conditions?*
43. *When it comes to respecting human rights, how satisfied are you with the company?*

Closing question

1. *How have you experienced the conversation?*

Transcription of the interview

Transcript label

Filename: Follow-up meeting Future GmbH Ecorus-20220802

Interviewer: Jan Roelofs

Location: Online via Teams

Date: August 2, 2022

Duration: 36:42 min

Transcription key

I = Interviewer (Jan)

P = Participant

(. . .) Pause

[sound] Sigh, laughter etc.

(inaudible) Unclear speech

[[____]] Redacted text for anonymity

word emphasis on a word

Complete introduction was done before the recording.

I: Thank you for reserving some time. I believe that you have some specific knowledge that can contribute to my research. Uhm, also I would like to emphasize that everything you tell me is completely anonymously. So also your name will not be mentioned in any documentation. Uhm, do you have any questions, uhm, before we begin?

P: Not now really [laughter]

I: Okay, great. Let me begin then. Maybe the questions are a little bit awkward because the questions I would like to ask are related to human rights, and, uhm, labor conditions. Uhm, but as I mentioned earlier, it is not to blame you of anything, uhm, so these questions are also based on a standardized set of questions based on the United Nations. Uhm, so that is also the reason why you might think these questions are a little bit awkward or something like that.

P: Okay.

I: Okay, then I will just start. Uhm, so for how long have you been working at, uhm, it was since 2007, right?

P: Yeah.

I: Uhm, and, uhm, Future is recruiting, uhm people from Russia, Ukraine, and other east European countries, right?

P: Uhm, not future. Our subcontractor.

I: Yeah, indeed.

P: Yeah.

I: And could you explain what the recruitment process is looking like? So how are the people recruited and based in, for example, The Netherlands.

P: Uhm, our subcontractor make the recruitment for the people. And our subcontractor has, has, uhm, uhm, is set up in Poland. And, uhm, their (. . .), I think, uhm, at their it is so that their guys come and want to work and then the (inaudible) in Poland check uhm, what can they do, what can they good do, and what can they not good do. Okay, they get, uhm, uhm, they get safety instructions, and also what we would do in Germany, or the Netherlands, and what the work will do. They get the, uhm, the specific touch to (inaudible) to work with. And what, uhm, and to see what they have to look for, yeah.

I: Okay. Okay, clear. And for how long are the employees in the Netherlands, or in Germany? Is that a entire year or a certain part of the year?

P: No, if it are good workers we want to hire them and then they work not only the whole year, maybe two or three years. I don't know. If they want to stay with us or with the company, then they get the same like, uhm, uhm, that we work for them and they get holiday and they go at home, and they come back and work. It is not, uhm, that we said that you can only work one year. We said if you are good, you can work with us all the time.

I: Okay, make sense. Uhm, and you also mentioned that, uhm, the workers, I can say it like that, right?

P: Yeah.

I: Uhm, that all joined the company in Poland. So all the employees did join the company the organization by their own choosing?

P: Yeah.

I: Okay, great. Uhm, and, before going to the Netherlands or Germany. Are the employees able to negotiate or are free to negotiate their contract in terms of salary, or days off, or something like that?

P: Yeah. That is no problem. They are free.

I: Okay. Great. Uhm, and are employees also represented in a collective agreement?

P: Yes, yeah, yeah [laughter].

I: Great. Short and clear answer. Thank you. This might be an awkward questions but this is a standardized set of questions. Are you known with child labor within this organization, uhm? Are you known with this?

P: Uhm, I am not sure [laughter].

I: Could you maybe elaborate on this?

P: Uhm. I don't know. Maybe I didn't understand what you mean [laughter].

I: Okay. With child labor I, uhm, the definition of child labor is that children are working at a company which are under the age of eighteen which are working constantly for 40 hours a week.

P: No, no. We didn't work with, uh, children, we must work with men and they are over eighteen. And sometimes they are twenty or twenty-one. And now I think we, uhm, now have with our subcontractor, uhm, 300 men and there is now under twenty.

I: Okay. That make sense. It was just to make sure that this is excluded. Okay great.

P: Yeah.

I: Have you ever experienced unpaid labor within the company?

P: No.

I: Okay. Clear. Uhm, are you familiar with deductions on wage of employees that were enacted for unclear reasons?

P: Uhm, maybe you, uhm. That I am not know what you know. Maybe you can clear it for me.

I: Sure. So normally every month you should get paid for the hours you have worked in the month.

P: Uhuh.

I: But are you familiar that this wage is deducted? Or that people are not getting paid according to the contract.

P: No. Uhm, (inaudible). Is hired by our subcontractor every month. Maybe if we have so many workers now, they are getting paid every week. So they got every time money and they send money to the family and for use, it is very, uhm, such a big point that they can get the money to the family so it is not work, work, and work, or something else. So for use, money is a big thing and they get send it to the family.

I: Okay. So you suggest that all the money is transferred to a bank account?

P: Yeah. Right.

I: Okay. And in terms of the salary. The employees are getting paid by the company. How is it arranged with the minimum salary according to the law? Are the employees covered by German laws or laws that are, uhm, present in their home country? How does that work?

P: That is present where they have the contract. So, uhm, now they get from Poland. So it is a little lower than us. But not that low compared to Ukraine (inaudible). In our work it is so that they get (inaudible). But they get the money from Germany if they are good and work hard. Then we pay the money from the law of Germany.

I: Okay. So only if the workers are working appropriately, then the recruited by the Germany company and then they are represented by German laws?

P: Yeah.

I: Okay. Uhm, and, every month are getting paid. Are they also getting a clear overview on how the salary based upon?

P: Yes.

I: I also asked these kind of questions to Yasin. But what is the average worked hours in a week?

P: In a week, I think, sometimes it is summer, and the days got longer. They can do much more work. I think not over 40 - 50 hours per week.

I: Okay. And are they also working on Saturday or only from Monday till Friday?

P: That is dependent on the customer. If the customer say that is no problem. Then you can work on Saturday. Maybe the project must be finished and then they work Saturdays. But it is not normal. Normally is from Monday till Friday.

I: And in terms, the average number of days off or holiday I would say it. Are you known with the amount of days the workers can take?

P: Yes, for the normal workers it is 24.

I: What do you define with normal workers?

P: Yeah, I think, the guys from (inaudible) they do more in a quicker get a little bit more holidays. They get, uhm, thirty days in a whole year and the normal workers get 24 days in a year.

I: But why do you make between a distinguishment between those type of workers?

P: Uhm because we have such a teams, uhm, that they want to make more money in a quicker time so they work at (inaudible) and they work more and the days are longer for them. So we said okay, if you work so good, you make your money, you be so fast and work good, you get more holidays and free time. For that guys, they must chill and see the family and everything else. The normal workers, they work two or three months and then they drive back to the families. But the workers from *Ardas*, work for six months, nine months and then they got a home and they are home for the rest of the year. So they don't see their family so much so we said, okay, if you want to do that and you are a good workers, we give you more free time. For us, it is very uhm, the employers are the best and also the works, we need them all time. So we give them a good chance, if you are good and fast workers, you get more holidays and more money.

I: And what type of nationalities are joining the Polish company? Are you known with that?

P: I think, uhm, the biggest part is Russian and Ukraine. Somethings it is Letland. Not any other countries I think. These three [laughter].

I: I am curious. How does an employee from Letland join a company in Poland? How does that work?

P: Uhm, yeah, I think that has the do with us. Because I think in Poland we have such a good nname and every men know you can good work with Future and you can get good money there. So sometimes men from Letland comes to Polish company and then come to us and then work here. That is not, uhm, that is not a big part. We also have guys from Letland there.

I: Okay, but do you also recruit by online things, like LinkedIn or something like that?

P: Yeah, not now. But maybe in the future it is a part about that.

I: Okay. Going back to the questions. Are all employees covered by a health insurance

P: Yeah. Yes

I: Same questions, other context. Are all employees covered by a retirement insurance?

P: Retirement insurance? Uhm, uhm. I need a little of help. What is retirement?

I: Uhm, you are retired, that is also country dependent. But in the Netherlands you are retired from 67.

P: Yes, yes now I know. Yes, yes, they are.

I: Okay. I though you already mentioned it. Are there any company level safety certifications, for example, V.C.A.?

P: Yes. For us in Germany, SCG. But all employers should get that and our company get that and get a certifications.

I: And is it also the case that before employees are allowed to work, that they have to get a certifications?

P: Yes. Every one [laughter].

I: But although all employees have a certifications, have you experienced any hazardous or dangerous working activities? For example, working without protective gear?

P: Yeah, I think, our work stuff the only big thing is work (inaudible) roof.

I: What is that?

P: (inaudible). That is, uhm, stuff like, uhm, they can build in a roof. Very old stuff and it is called (inaudible) and it is such breakable. That is not so much work there. Only flat roof or something else. I think there is no big reasons if you go there, uhm, you hear about your project leader, the reasons are not that big for you.

I: Okay. You are not familiar with any deaths during working activities?

P: No, no, no.

I: Okay. And in case such a dangerous situations was reported to the company. Has the company taken appropriate measures to, to address these?

P: Yead, that we have. In the time I am here, I think one situations was occurred.

I: But during that time, the company taken appropriate measures?

P: Yes.

I: Uhm, uhm, another question related to the safe working activities. Uhm, is there always and consistently safe equipment for all workers. For example, helmets, safety shoes.

P: Yes, Yes. VCA. [laughter].

I: Before starting with the working activities, they should always, uhm, these helmets and safety shoes.

P: Yes, yes.

I: Were all employees, uhm, trained before starting with the working activities? For example, if one employee is introduced with the stuff they have to do. How does such procedure looking like?

P: Before they start, they get a instructions about that. They are not allowed to start before they the instruction is clear for him, before he knows what he do in what situation, what he must wear, shoes and everything else, uhm. They got also every time when they get new projects, instructions by the project leader and he says you can go there, uhm, there where you can smoke or go to the toilet, and they are not allowed before that is done.

I: Good to hear. Uhm, Okay. Another questions, that is related to another topic. To what extent have the employees knowledge about the language and laws about the country where they are located? Are they getting educated or something like that?

P: Hmm, I don't think so. I think when they, uhm, got to our subcontractor. Maybe he speaks Russian, and, uhm, for us, on the project every time he get the Russian question. When he want to know our language, no problem, we help them. For us, they got their own language [laughter].

I: But is there always somebody who can speak English?

P: Yes, yes.

I: Question related to the housing because all the employees are located in The Netherlands in case of a project in the Netherlands. Did the company fix the housing of the employees?

P: Yes.

I: So everything is arranged by the company?

P: Yes.

I: And how many housing options did the company provide? Is this only one or are they free to choose?

P: No, yes, they are fee to choose. If they said, for me it is not possible to sleep with him in a room or something else, they can choose. But that clears the project leader at the site and the houses they live for. But every time they feel free, if they say, okay, I need a room by myself for calling the family or live. That is organized by used and every time, it is so organized that they got such enough room, uhm, for their self.

I: What type of housing is provided? Is that a hotel or a vacancy houses?

P: I think, uh, for the long times, every time it is a vacancy house because there they can cooking and bathroom and sometime else. Hotel is not so good because our project are not so tiny. Every time we have big project so they stay there for one month or more, uhm, uhm so they get vacancy house so they can cook and live, and yeah.

I: Okay, okay. I am not sure whether you know this, but do all employees have a own room?

P: Yes, yes. Sometimes if they are good with another, the get a two-room, but normally they all get their own room.

I: Okay. Uhm, are you known with a mismatch between what was promised in Poland and what the employee had to do in the Netherlands?

P: I don't think so. The company is Poland is with us such a long time so they really clearly know what they do and I think, uhm, and now it is in Poland that they are in a little (inaudible), under construction type. So the employers can see, that is the under construction, you must do that. Then they also have the models and they can take and they can say, uhm, this is too much for me, too much weight for me. They can also say. But, uhm, Poland they have constructions and models and show the employers, okay, this is your work for the next month.

I: Okay, then it is quite clear for the employees what they are going to do in the Netherlands, for example?

P: Yeah, yeah.

I: Okay, right. Uhm, and the same holds for the housing. Are all employees known with, uhm, where they are going to live in the Netherlands. Are you known with a mismatch between that. Or is that also clear for all employees?

P: No, I don't think so. Uhm, maybe in the Netherlands, or something else. The vacancy house are sometimes better than in Poland. But, uhm, the project leader clear that at the first time when the project started, then, also have, uhm, pictures or something else. That they can say, okay, uh, there we can live. Do you want this room or that room? I don't know. Uhm, the, the, project leader clears this every time and then it is clear where they live. And there you can speak with the employers. I think if they come here and work in the Netherlands, and, uhm, it is so much better than in Poland.

I: Okay, okay. And related to, uhm, free moving. Are employees completely free to enter and exit the living, the housing?

P: Yes.

I: The same holds for free entering and exiting the site, the working location.

P: Yeah, yes, yeah.

I: I can imagine, for example, if employees are transferred from Poland or Ukraine to the Netherlands, or Germany, or wherever. Uhm, I can imagine that they are a little bit isolated from the rest of the society. Are you known with that employees are feeling isolated from the society or from the local communities?

P: I don't think so. Now at our companies it is so that we have groups of employers and, groups are, uhm, uhm, always be the same so the employers know each other and can go and have free time. I think in such a group where everyone knows each other, it is little bit better for them to get the local things or got every other person to know, or to meet. I think if that groups, it is little bit easier for them.

I: Okay. Great. I think this is important to address. Have you ever experienced physical or sexual violence among the employees?

P: No, no. We only had men in groups because we didn't have any female employers. Only one or two but they didn't work on, uhm, sites with so much men. Because if we had, uhm, girls here or women, then we look about their time and peace. Really, uhm, approved about that. It is not really good girl job we think about. We also tell the girls that they have to do, okay, that is your work to do. But if we have girls or women want to do this work. Far from our company that we can drive to. And check if everything is okay for them. Is it too hard for them.

I: Have you experienced intimidations or threats for the employees?

P: Uhm, I need a little bit of helps.

I: Treats is a, uh, for example, if you don't this, then you don't get paid. That is a treat.

P: I understand it. No, I don't think. They got the rules and we always say tell the rules. Uhm, also the rules in the vacancy houses, where they live. But if they break such rule, or I don't know, they must pay it by their self. But we don't say, if you do that, you don't get no money. That is not nice for them and I think we want to (inaudible) the people at the time and want that they work the whole year, and I think we said that to the employers. Uhm, maybe, such employers said, okay I don't want that. If they are really good men, so, I think that is not fair. So we say, if you broke something or you broke a rule, uhm, and, uhm, somethings something break then you pay it by yourself and everything is okay.

I: Uhm, let me see. Have you ever experienced that employees worked in order, uhm, pay their debts for the company?

P: No, I don't think so.

I: And you also mentioned that they were two women that were recruited for the company. Uhm, are you known with differences in salary between men and women?

P: No, not really. For us, it is so, if a women is interested in a job, the job is the same for women and a man. Sometimes we can use it so that we can't take the big models. Then they got a little bit easier work but not all the time. If a women says I want to work with you and I want to work there and they know what the work is. IF they want to do it, the get the same as the guys.

I: I already asked you questions related to living and working conditions but also related to human rights. But how satisfied are you in with the company in terms of realizing appropriate working conditions?

P: Uhm, appropriate working conditions? I need a little bit of help

I: Appropriate is good, proper, is satisfied.

P: I know. Such a good thing [laughter]. For us in our company, with this workers we have, I feel it is good here. And I also think the employers, that they, uhm, learn that our company works so and then they get more money and free time. I think they also feel good about that.

I: The reason why I asked this. Generally, uhm, employees that are, uhm. For example, people from China or East Europe which are recruited and then located in the Netherland and then they have to perform working activities are more, how would I say it. The chance that human rights are violated from East Europe people is higher than, for example, Dutch employees. For example, they cannot speak the language, or bad living conditions. That is also the reason for asking these questions. So do you see any opportunities for the company to improve working conditions, living conditions, or any other human rights?

P: Okay. Uhm, I think, now, this time we do much more about that because now you know about the war in Ukraine. We have much workers from Ukraine and so, uh, in this time, we say they can here with us in Germany. We got much of this people, uhm, in our company and they now work for Future, not for the subcontractor. They live here in Germany. We search for the houses and everything else. For the kids school. I think that is really type from us, from our company. That my CEO look and want to help and everything make the things for the employers better. They want to like the work with us.

I: Okay. If, if, for example, if the Ukraine people are recruited by the Polish company and they are working quite good for a year. Then they are represented by the German company and are represented by German laws and in that case, then sometimes the families are also coming to Germany. Is that a common thing?

P: Yeah.

I: You answered all the questions quite good in terms what I would like to see. Ecorus is also striving to ensure this over the entire supply chain so no human rights are violated. Uhm, yeah, but maybe the questions are a little awkward. So how have you experienced this conversation?

P: For me, it is okay. I think you are not the first that ask these questions. This company wants to do something for human rights and the workers. I think it is good that you ask these questions. Uhm, but, it is got more and more about the companies that they know this information. For me it is okay. If companies asks these questions, more companies do that for the employers. I think the life for the, uhm, employers got a little bit better.

I: Yeah, absolutely. I heard some stories because I also did some research about human rights violations among employees and also East European employees and yeah, it occurs quite often that there are bad living and working activities. That is also the reason why Eocrus is striving to, uh, ensure that there are appropriate living and working conditions. Thank you for reserving some time and answering these questions. You helped me a lot. And uhm, yeah, I am sure that Ecorus is really happy about these outcomes and hopefully we can strengthen the relationship between Future and Ecorus. So thank you for that.

P: Thank you. Have a nice day. Bye bye.

I: Bye.

Summary of interviews with solar supply chain expert

In order to evaluate the social and environmental impacts of a PV module, it should first be defined which processes are included in the study. Could you please elaborate on how a PV module is produced, starting with extracting raw materials till constructing the actual panel? Could you explain which phases are there? What is your impression about the supply chain sketch below?

- Visualization Figure 3.2 of the supply chain is an appropriate representation of reality
- General supply chain: quartz, MGS, polysilicon, ingots, wafers, cells, modules
- No vertical integrated supply chain from quartz to modules so far by one producer. A good example of plans to do so are the Indian projects (Adani, Reliance and SSEL) and Hoshine in Xinjiang.

As far as I am aware, this supply chain can be divided into the chain that provides the polysilicon, and the chain that manufactures the modules. As far as I know, big PV module manufacturers, such as JA Solar, Longi, and Jinko Solar, manufacture ingots, wafers, cells, and modules. How do you see this from your perspective?

- Nowadays, the solar industry is often visualizing the entire supply chain by starting with polysilicon and ending with the module, ignoring the raw materials and MGS processes. Three reasons for neglecting these processes: (1) not aware of these production processes; (2) it opens up inconvenience issues (mainly in terms of where the MGS was produced and, perhaps, where the quartz was produced – most "analysts" fail to understand that MGS can be shipped economically great distances from point of production to point of consumption so Xinjiang MGS and other Chinese MGS is used by Wacker in Germany for example; shipping quartz long distances is not as economically favorable but is done (Spain to Norway; Spain to Canada; Poland to Iceland; India to Malaysia for example); and (3) environmental impact would be significantly increased (since coal is used to produce a good percentage of global MGS including all in Xinjiang)
- Supply chain: MGS process should be added
- Table 4.3 with the geographical location of polysilicon, ingots, wafers, cells, modules (provided by Bloomberg) is quite accurate. However, two columns should be added: (1) quartz; and (2) MGS. Regarding quartz, there is no reliable data about quartz supply (quartz supply to

MGS has never been viewed as an important thing to track until now with Xinjiang – quartz impact on MGS quality is addressed by MGS purity specs) so expanding the table with quartz would be though

- Total Chinese MGS production is 2.8 million tons in 2021. For which:
  - 38% is produced in Xinjiang
    - 20 MGS smelters
    - Not visited by Alan
    - Practically all quartz is coming from Xinjiang
    - Often coal-fired electricity is used for this process
    - High level of certainty: every MGS producer in Xinjiang uses quartz from Xinjiang
    - There are around 20 smelters in Xinjiang and produce million tons of silicon last year. Of these million tons, about 550,000 tons were consumed in Xinjiang. This implies that 450,000 tons were consumed somewhere else. Some of this may go to XJ aluminum, other China aluminum or exported for Al but the Al industry usage is likely low as the iron content of XJ MGS is high so only suitable for lower value secondary Al. Assume most of this excess Xinjiang goes to most other Chinese poly producers (except those in Sichuan and Yunnan), the other two Hoshine silicone plants in China, some amount to almost all other Chinese silicone producers and also some exported to silicones and polysilicon (exports would be focused in Asia such as Japan, Korea, Thailand).
  - 20% is produced in Yunnan
    - 54 MGS smelters
    - Significant visits by Alan
    - Most, if not all, quartz is coming from Yunnan (some quartz may come from Myanmar; most charcoal required for the MGS production comes from Myanmar – forced labor is a problem in Myanmar including some evidence in the charcoal industry). Highly unlikely that they use quartz from Xinjiang since quartz is present in this region.
    - All (almost all?) Yunnan MGS smelters use local, seasonal hydroelectric which means most smelters only run 5-7 months out of the year during the rainy season when local, low-cost hydro is available. Grid power (mostly hydro but some coal) can be used but cost is too high.
  - 17% is produced in Sichuan
    - Some visits by Alan
    - Highly unlikely that quartz is used from Xinjiang. Most likely from Sichuan
    - Local Hydroelectricity is used for this process.
    - Tongwei Polysilicon (largest poly producer in the world with most current capacity in Sichuan) is based here and uses probably 100% Sichuan MGS made with 100%

Sichuan quartz. Tongwei could use non Sichuan MGS if there is a shortage from Sichuan (perhaps in 2022 due to no rain).

- 4.5% is produced in Inner Mongolia
  * Likely that there is also quartz but amount and quality not known.
  * Present Inner Mongolia MGS production, with perhaps some small exceptions, is low quality and only suitable for secondary aluminum alloy production.
  * Huge increase in MGS capacity in this region is planned to go along with the significant massive polysilicon expansions announced for Inner Mongolia (along with silicone expansions).

- Required quartz for Chinese MGS producers is also coming from Chinese suppliers. Highly unlikely that Chinese are importing quartz NOW but this may change as the MGS demand / production increases.
- The main problem to formally link the Xinjiang region to forced labor is that no official documentation exists.
- The location of quartz is often close to the smelters (see prior comment).
- Other examples of quartz mines are Spain and India
- Quartz is often first transported via rail and then this is trucked
- In case of the MGS is produced in Yunnan or Sichuan, drought can result in no hydro-based electricity, so the power should come from the Chinese grid. However, historically, the plant is shut down since it is too expensive to operate. So if this is shut down, they could buy MGS which is produced in other parts of China.
- Before the last two summers, it was believed that no forced labor was involved in the Yunnan and Sichuan regions. But, in the case of drought periods, one of the leading sources (provinces) of non-Sichuan or non-Yunnan MGS is likely to be Xinjiang based entirely on MGS production in each of the provinces.
- Hoshine might supply MGS to almost all polysilicon producers in China (except Tongwei Sichuan and Tongwei Yunnan in normal cases when local MGS is available; Hoshine has listed Tongwei as a customer so this is likely the Tongwei poly plant located in Inner Mongolia)
- Jinko is the only module manufacturer with a fab in Xinjiang
- Chinese polysilicon (any polysilicon) can be transported all over the world but almost all is consumed in China. Some is going to the Chinese operated ingot / wafer fabs in Cambodia, Malaysia, Thailand, Vietnam which were established to serve the USA market to avoid USA tariffs on Chinese produced cells and modules.
- Zero transparency regarding the location of extracted raw materials (extremely confidential)
- Operations by all big solar companies with no facilities in Xinjiang are not involved direclty with forced labor but indirectly use forced labor if they use quartz, MGS and or poly from Xinjiang.
- Easy conclusion is that at present, practically all silicon-based solar modules sold in the world have a high chance of containing some silicon that originated in Xinjiang as quartz

- Companies that focus on ingots till modules don't produce polysilicon so they all buy the required polysilicon. This is the point where no transparency is there
- There are four poly producers presently in Xinjiang and they are only using MGS from Xinjiang
- Tongwei (around 20% of Chinese polysilicon production) is not buying from Xinjiang because there is silicon in Sichuan and Yunnan Tongwei is out in normal circumstances so has a clean supply chain. However, they also have some capacity in Inner Mongolia and there is a little bit of MGS in this region, but most of this is consumed from other provinces Xinjiang. If Tongwei really wants to report that they are not linked with Xinjiang, they would probably report this but there is no data at all.
- PV manufacturers won't be transparent in tracing their supply chain (due to confidentiality)
- There exist bar codes for, for example, ingots and they indicate the date of production, and where the polysilicon comes from (supplier). The ingots manufacturer would theoretically know where the polysilicon comes from but they are not worried about the MGS going in (as long polysilicon meets the requirements).
- The fact that PV module manufacturers don't publish their operations and supply chain in the public domain, they are practically all guilty
- "If polysilicon is not produced in Xinjiang, then it has no Xinjiang components" is completely wrong.
- Three requirements for silicon smelters location: (1) low-cost energy; (2) high purities; (3) close to where the quartz is coming from. Quartz is relatively low value and the transport costs can quickly get higher than the value of the quartz
- So far, unsuccessful to identify where the quartz is coming from. Most likely in the Eastern of Xinjiang (on the border of Kansu). Highly likely: most quartz is coming from the east of Xinjiang and most smelters are located in the West of Xinjiang so this quartz is transported by rail
- Highly likely: some on non-Xinjiang polysilicon (other than Yunnan and Sichuan) smelters are using quartz that originates from Xinjiang

You mentioned that at the time the report of Laura and her colleagues was published in May 2021, you have been spending a lot of time trying to better understand the entire solar silicon supply chain. Furthermore, you mentioned that your easy conclusion is that at present, practically all silicon-based solar modules sold in the world have a high chance of containing some silicon that originated in Xinjiang as quartz. While Laura Murhpy concluded that polysilicon manufacturers in the Uyghur region account for approximately 45% of the world's solar-grade polysilicon supply. Could you explain what made you come to your conclusion and what is the chance that imported Chinese PV modules can be related to the Uyghur region?

- 45% of Chinese polysilicon is made in Xinjiang so this might suggest that only 45% of the PV modules can be related to forced labor. However, this is not true since indirect operations can result in linkages with Xinjiang.
- German polysilicon producer, Wacker, imports MGS from China. A couple of years ago they used Hoshine MGS which is located in Xinjiang. Wacker never formally said (when the

information was published in May 2021) they were going to stop using Hoshine MGS.

- MGS can be used by other polysilicon producers which are not located in Xinjiang. For example, Tongwei (not located in Xinjiang) could imports MGS from Xinjiang or any other Chinese province (Xinjiang is likely based just on how much MGS is produced there) in case there is no cheap electricity.

You also mentioned that you have been to most of the MGS smelters and that you visited perhaps 100 Chinese smelters since 1999. Unfortunately, you never made it to Xinjiang. I am wondering what your findings were when visiting these smelters. From which regions was the quartz coming, perhaps also coming from Xinjiang?

- For non-Chinese smelters, nobody is using Chinese quartz.
- When comparing non-Chinese smelters built with the lowest standards (e.g., Brazil) they are still better than the Chinese highest standards in terms of environmental perspective.
- Highly likely (99.9% sure), during the visits of Alan, no smelters used quartz from Xinjiang.
- Never seen child labor

From your perspective, although you never made it to Xinjiang, what is your impression of this region? Do you foresee a big chance of forced labor present in this region? Could you elaborate on your impression of this region?

- Very complex to conclude on this

More and more attention is paid to corporate social responsibility and following the 10 principles of the Global Compact by companies. This implies that companies proactively support and follow internationally proclaimed human rights, no forced labor is involved, no child labor is involved, no discrimination occurs, no corruption is present, and no dangerous emissions are polluted during the production processes. What was your impression of the smelter companies that you have visited in terms of these principles? In other words, what was your impression in terms of these topics when you visited the smelters in China?

- Again very complex to conclude on this
- The audits at these smelters might be misleading since these companies are prepared and know that visitors are coming (everybody wears safety glasses)

This question relates to laws and regulations. Did all smelters companies that you visited comply with local laws and regulations on labor, and human rights? For example, did all employees have a contract, were all employers insured, were paid with the minimum required by law, and were paid on a regular time basis?

- For example, whether the employees are insured, you never know
- Hard to identify the truth.

This question also relates to laws and regulations. What was your impression when visiting these companies in terms of health and safety? For example, have you ever experienced excessive working days or extremely long working days, was the safety equipment constantly available, have you ever experienced dangerous working situations?

- Hard to identify the truth

Are you known for prosecutions of these smelter companies in connection with any environmental or social-related incidents?

- Not aware of prosecutions

Since the solar supply chain is all interconnected, for example, forced labor in the Uyghur region can result in solar panels that are manufactured by forced labor and exported to Europe. Do you see any differences in respecting human rights, or any other social performances among different PV module manufacturers, for example, JA Solar, Lungi, or Jinko Solar? What PV module manufacturer do you recommend for European companies to import?

- No, Alan considers them all guilty
- There is no supply chain transparency
- Jinko Solar (has operations in Xinjiang), and probably others, are in the process of establishing a parallel supply chain, just for the US market. This is obviously because of Xinjiang, but they won't say this. So Jinko will set up this parallel supply chain, where polysilicon is made by, for example, Wacker with non-Chinese MGS (probably produced in the US), shipped to Vietnam and Jinko makes the ingots and wafers, cells, and module (so no Xinjiang). But at the same time, the company is operational in Xinjiang via the other supply chain.
- Most encouraging in Europe in Northern of Norway where an ingots/wafer fab is built and making ten times expansion. The remaining percentages of ingots and wafer fabs are located in Norway.

Ecorus is the second largest solar developer from the Netherlands and is mostly importing modules from JA Solar. What is your impression of this company?

- Following table is from public domain (based on contracts)
- Contract valid till 2023/2024
- Pretty definitive that this company uses quite a little bit of Xinjiang
- They don't own facilities in Xinjiang. However, JA Solar is buying materials that can be originated from Xinjiang
- JA Solar is also guilty as charge based on the table

JA Solar - Polysilicon Supply

item	PR Date	Poly supplier	Tonne Poly	Start	Stop	Total Months
1	8/24/20	Asia Silicon (Qinghai)	19,800	Sep-20	Aug-23	36
2	9/15/20	Xinte (Urumqi, Xinjiang)	97,200	Oct-20	Dec-25	63
3A	12/28/20	Daqo (XUAR) - low end	32,400	Jan-21	Dec-23	36
3B	12/28/20	Daqo (XUAR) - high end	43,200	Jan-21	Dec-23	36
4	4/21/21	Asia Silicon (Qinghai)	75,000	Sep-20	Sep-25	60
5	5/12/21	Daqo (XUAR)	78,200	1-Jul-2021	31-Dec-2025	54
6	6/21/21	Xinte Inner Mongolia	Not provided	Not provided	Not provided	

Asia Silicon MG-Si at least some comes from XUAR

-

Am I allowed to use the data you provided my in your previous email, indicating the poly supply for JA Solar?

- Yes

Summary of interview with first embassy secretary at the Economic Department within the Dutch embassy in Beijing

Introduction

1. The main objective of this research is to identify the supply chain of Ecorus and assess these on environmental and social impacts. These outcomes will be incorporated into the sustainability report of Ecorus.
2. Two main goals of this meeting: (1) verification of the supply chain; (2) identification of possible social impacts in the supply chain
3. Introduction embassy representative: specialized in business and human rights

Figure 4.2 visualizes a high-level solar supply chain. Based on this figure, the location has been identified and its conclusions are presented in Table 1. Do these results correspond to your knowledge? And what is from your point of view the part of the supply chain that results in limited transparency?

- Xinjiang and Tibet are the provinces where human rights concerns are the strongest, and where there is strong surveillance in place, which can result in limited supply chain transparency

Based on Table 4.3, which regions/provinces in China are most critical and sensitive in terms of human rights violations and poor working conditions in the PV industry?

- Regarding human rights violations in China, hard to conclude on this
- Mainly in Xinjiang and Tibet provinces
- Companies will behave according to what the government instructs
- For a Chinese party to acknowledge that it breaches human rights would be unimaginable
- Limited transparency in Xinjiang mainly due to: (1) this region can be considered as a policy state, implying high surveillance and practically everything is controlled by the authorities; and (2) corona restrictions so unfeasible to find concrete evidence for forced labor
- Performing audits in Xinjiang is unrealistic nowadays

Several solar industry experts believe that practically all silicon-based solar panels sold in the world have a high probability of containing some silicon that originated in Xinjiang as quartz. In other words, today all solar panels might be related to Xinjiang and thus forced labour. From your perspective, how do you interpret the current situation in China and Xinjiang with regard to human rights violations, working conditions, and forced labour?

- High risk of forced labor in Xinjiang, based on, for example, Sheffield University and ASPI. More importantly, the UN Human Rights Council's report published on 31/8/2022 contains a detailed account of the human rights violations in Xinjiang.

Are you known with Chinese companies that can be linked with non-compliance with respecting human rights?

- Refer to, for example, the Sheffield University paper and the ASPI reports.

Are you known with developments that resulted from the publicity regarding forced labor practices in Xinjiang? For example, huge production capacity expansions in Central Mongolia have been introduced and a separate supply chain for America is being set up currently.

- Inner-Mongolia: Daco indicated that the main reason for moving to this reason is that in this province is more renewable energy available. However, highly likely that another reason is that in this way they can't be linked to Xinjiang
- Another supply chain for the USA: mainly caused by the introduced regulation in this country that implies that no products can be imported that can be linked with forced labor.

A CSR questionnaire has already been sent to our main PV module supplier. To what extent are these results reliable in your opinion?

- Human rights: not reliable.These results are mainly influenced by: (1) government pressure; and (2) in China it is believed that no human rights are breached (not only due to propaganda).
- Themes like working conditions, corruption, and environment are taken very seriously in China so these outcomes are more reliable than the outcomes of the human rights questions. However, a questionnaire filled in by the supplier still cannot be considered reliable proof that CSR risks are covered, as no external party has checked their answers.

Our main PV module supplier develops and produces the ingots, wafers, cells, and modules mainly in the Jiangsu region. What is your impression of this region concerning human rights and working conditions?

- Colleague will come back to this via mail
- Generally, the province of Jiangsu is one of the richest and most developed parts of China, which might suggest that CSR considerations are more often complied compared to other parts of China

To determine the environmental impact of a solar panel, all processes (shown in Figure 1) have been included in the developed model. The energy mix used in the model heavily influences the environmental impacts. Do you have an idea of what the different electricity mixes look like in various provinces in China? For example, it seems that Xinjiang mainly uses cheap forms of coal-fired electricity. However, I have not found any official documents to suggest this.

- Most recent data can be found at the National Bureau of Statistics.
- Important to note that the concerning energy mix in the province is not by definition the same as the energy mix that is used in the supply chain since a lot of electricity is traded within China. Therefore it is crucial to identify the energy mix of the involved parties in the supply chain

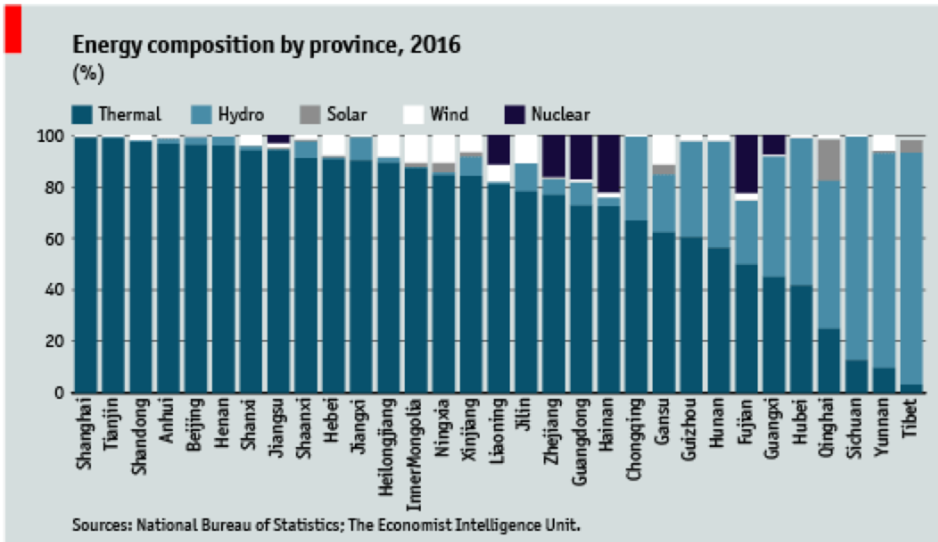


Figure 7.5: Energy mix in Chinese provinces

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Do you think that China is moving in the right direction in terms of working conditions, human rights, and anti-corruption phenomena?

- Working conditions: going in the right direction. For example, China is in the process of amending the Working Hours Act (to tackle structural overtime) and regulations to improve safety during working activities.
- Human rights: no. In all likelihood, there is forced labor and ethnic groups are systematically oppressed. Also concerns on freedom of association, freedom of religion, LGBTI rights, and gender rights.
- Anti-corruption: hard to say as corruption cases are sometimes rather politically motivated. However, much attention has been paid to corruption which seems to have resulted in less corruption. Results do differ per region. Developed provinces like Jiangsu may have fewer concerns than less developed regions.
- Environment: a lot has been improved in recent years. Strict environmental regulations. There are examples that foreign companies don't meet the environmental regulations in China. However, the energy mix does not seem to be improving yet as China focuses on coal for energy security.