Title picture: American public power association (https://unsplash.com/de/@publicpowerorg)

February 2023

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Executive summary

This project focused on Biosphere Solar's challenge of developing a sustainable and ethical supply chain for the production of their modular photovoltaic panels. The goal of this project was to develop understandable and easy to implement advice on which suppliers to partner with. The scope and strategy included three analytical levels (raw material level, component level, and supplier level). The focus was mostly on upstream supply chain processes, though end-of-life potential and operations were also included. In terms of raw materials, silicon, silver, copper, antimony, and tin were investigated. The main challenges differed for each material were mainly associated with material scarcity and monopolies, the environmental issues of mining, labour conditions and safety, toxicity, and non-renewable energy provision. Then, the incorporation of these raw materials into the components was analysed. Critical aspects of the glass were an energy-intensive manufacturing process and antimony content. The antimony could be replaced with CZTS (copper-zinc-tin sulphite), which is more abundant and non-toxic. For the wiring, copper was recommended as a replacement for silver because of a higher abundance and lower price, possibly in the form of a conductive back sheet instead of metal paste. 70% of the PV module's impact on climate change originates from the solar cells, mostly due to the energy used in polysilicon production. To reduce this impact, increasing the material efficiency of solar cells and using renewable energy during production are among the best practices. Ultimately, we developed a supplier selection tool based on multi-criteria decision analysis (MCDA). Based on questions in four categories (location, choice and efficiency of materials and/or components, energy use, and occupational health and safety), a scoring can be derived to help decision-makers at Biosphere Solar navigate through the trade-offs when picking suppliers. This actionable tool will advance Biosphere Solar towards its vision for a more sustainable renewable energy industry.

Consultant team

Six MSc Industrial Ecology students formed an interdisciplinary and international consulting team for this 5-month consultancy project. Each team member contributed to this work with a different background and previous experience.

Lina Martinez Luna – External communication

In her Bachelor’s in Industrial Engineering, Lina followed a minor in complex systems (Monterrey Institute of Technology and Higher Education). Afterwards, she worked as a consultant at KPMG Mexico (2.5 years). Lina brought the consultancy perspective, specifically for operations and supply chain strategies. For this project, she was the main communicator between team, commissioner and supervisor.

Luise Lehnerdt - Moderator

With a BSc in Biosciences/Life Sciences (University of Münster), Luise brought a solid foundation in the natural sciences into the team. Her professional experience during an internship in a sustainability consultancy was useful for the strategy and the formalities of a consultancy project. Her main role was the moderator, to facilitate group discussions and ensure an effective structuring of tasks.

Laura Vecoli – Scribe

Laura graduated from the Erasmus University College with a BSc in Liberal Arts and Sciences, majoring in sustainability and completing a minor in transformative change. Given her study background, she was able to approach problems from a holistic perspective by bringing together different disciplinary knowledge. She was the official scribe of the team but played diverse roles along the course of the project.

Maurits van der Wijk – Editor

Maurits graduated with a Bachelor's degree in International Business Administration from the Rotterdam School of Management (Erasmus University). After his studies, he interned at a consultancy, where he worked with a team to help develop a start-up from the ground up. He was co-editor of the final report, to ensure a high quality and consistent deliverable for our client.

Raquel Kuperus – Editor

Raquel received her Bachelor’s in Industrial Design (Eindhoven University of Technology). Her experience with innovation processes, along with her keen interest in developing circular and sustainable products was relevant given the nature of the project. By combining an analytical and systemic approach, she helped analyse the supply chain challenges. In the team, she was co-editor of the report.

1 Introduction

Photovoltaics (PV) are expected to produce the majority of renewable energy in the future (Ram et al., 2017a). However, PV module production is predominantly unsustainable. Various critical raw materials are required, supply chain processes are energy and labour intensive, and the modules mostly end up in landfills at their end-of-life (Farrell et al., 2020). To address these issues and work towards a new standard in the PV industry, Biosphere Solar is developing a circular and open-source PV module that can easily be repaired, refurbished, or recycled due to its modular design. Besides facilitating a closed material loop for photovoltaics, Biosphere Solar has the goal of sourcing their components from sustainable and ethical suppliers to eliminate human rights violations along the supply chain. Biosphere Solar aims to finalize their design and start pilot production by 2023 and have their product on the market by 2024 (Biosphere Solar, 2022).

To prepare for production, one of the main challenges Biosphere Solar currently faces is the need to define a supply chain. Low transparency and the complexity of the supply network result in a relatively high level of uncertainty. With the goal of minimising the environmental and social impacts of PV modules, a guiding framework for the selection of sustainable component suppliers is crucial, leading to the following research question (RQ):

How can Biosphere Solar navigate through the trade-offs of establishing an ethical and sustainable supply chain for PV module components?

To guide our research, this question was split over the following sub-questions:

I. *What are the sustainability challenges surrounding PV module raw materials?*

II. *How do the material level findings aggregate in the component level and which additional upstream and downstream sustainability issues exist for the components?*

III. *Which guidelines can be used to select component suppliers?*

With this study, we aimed to facilitate the process of setting up a supply chain for Biosphere Solar. Our vision was to create a guideline which delineates criteria for the selection of suppliers, based on the sustainability and ethics of their operations. This guideline provides a single, practical overview of the steps necessary to seek out suppliers that align best within Biosphere Solar’s vision of sustainability. The guideline is evidence-based and synthesises analytical findings to provide a clear and actionable decision tool.

2 Methods

2.1 Scope

For the raw material level, we focused on the upstream sustainability issues, while for the component level, we also investigated end-of-life options. While a life cycle assessment for Biosphere Solar's product is beyond the scope of this study, the investigation of raw material and component sustainability issues is a basis for a more accurate impact assessment and design validation in future research. Further, in line with the commissioner's needs, we excluded prices of the raw materials and the manufacturing from this research. The focus was mainly on environmental and social implications, transparency, and supply security. However, price will be an important consideration in further research.

2.2 Method for raw material and component level

For the raw material and component level (RQ I, II) we prioritised scientific literature research, but complemented our findings with grey literature (reports, newspaper articles, etc.). Two expert interviews were conducted to validate the information found in the literature and to guide and facilitate the literature research. The experts were Dr. Thorsten Dullweber (Head of photovoltaics department, Fraunhofer Institute, DE) and Amelie Müller (PhD candidate Industrial Ecology, Leiden University).

2.3 Method for supplier level, multi-criteria decision analysis

For the supplier level, we made use of multiple-criteria decision analysis (MCDA) under a qualitative approach to develop an Excel-based decision tool. The first step consisted of defining the criteria to evaluate each possible supplier. Furthermore, a list of questions was developed for each criterion. These questions can be answered by Biosphere Solar to derive a grade based on the direct rating technique method. This method, according to the "How to develop the decision recommendation" lecture, helps to normalize the data on a scale from 0 to 1, 0 being the worst performance and 1 being the best performance (Cinelli, 2022). Furthermore, criteria weights have to be defined based on the point allocation method; for this, a decision-maker allocates a weight to each criterion. The higher the number, the more important the criterion is (Odu, 2019). Finally, the computation of the global value is calculated with a weighted average score. The higher the number, the better the possible supplier. A detailed practical instruction can be found in the attached Excel file, which contains the decision tool, and in chapter 5.

3 Raw material level

The focus was on the raw materials identified as the most important by the commissioner, namely silver, tin, copper, silicon, and antimony. Each material was analysed with regard to all three pillars of sustainability (economic, environmental, social), paying special attention to the problems that could arise when having them in the PV module supply chain.

3.1 Silver

Silver has been mined as a rare element for 5000 years (The Silver Institute, 2022). At present, around 1,270,000 t have been mined (Figure 1). The countries with the highest production are Mexico, China, and Peru. Also, Australia, Poland, Bolivia, Chile, Russia and the US are exporters of silver (Sverdrup et al., 2014). A smaller share is produced by Sweden, Indonesia, Morocco, and Canada. Only 27% of the globally mined silver is primarily mined, all else is mined as a co-product with zinc-lead, gold, and copper (The Silver Institute, 2021). Investors have become increasingly focused on environmental, social, and governance (ESG) factors in silver mining, so the industry is paying increasing attention. For the green transition, silver is essential for electric vehicles and the charging infrastructure, and for solar PV modules (EY US, 2021).

In PV modules, silver forms contact threads as an electric connector because of its high electrical and thermal conductivity. It makes up less than 0.1% of the solar PV module and has relatively low cost compared to other materials (Ansanelli et al., 2021; Long et al., 2021).

Figure 1: Silver in its metallic form

3.1.1 Environmental issues

Only 16% of the energy supply for silver mining is from renewable sources, while 58% are from diesel and 21% are from non-renewable electricity (The Silver Institute & Metals Focus, 2022). In the future, electrification of mining equipment will be essential for lower emissions and better energy efficiency (EY US, 2021).

Silver mines need to responsibly manage their waste, wastewater, and water supply. An important aspect is also attention to biodiversity on the mining site and restoration measures of the ecosystem after the mine closes (EY US, 2021). For example, in Sweden, land use and licensing for mining sites is relatively strict and requires external audits (Svemin, 2022b). Mexico has established environmental regulations on the establishment of new mining sites (KPMG International, 2013).

In order to isolate the silver from the ore a common process is heap leaching, where a cyanide solution is sprayed onto the ore. The process has a relatively low water consumption, but the cyanides can accumulate and get into the groundwater (Ayres, 1997; Thenepalli et al., 2019).

Since colonial times, mercury has been used to isolate silver particles with the amalgam method (Hagan et al., 2011). The mercury vapor eventually condensates and the formed methyl mercury is toxic to aquatic wildlife, polluting waterways (Ayres, 1997; Garcia-Guinea & Huascar, 1997). This has destroyed entire landscapes such as the Potosi mine in Bolivia. Gold mining is one of the major mercury pollution industries in the world, the process is equivalent for silver mining (Ayres, 1997).

3.1.2 Social issues

Labour rights, health, safety, human rights, conflict management and community development have been identified as the major social challenges to pay attention to (EY US, 2021). In Sweden, trade unions and companies cooperate well. They manage to minimize accidents and eliminate work-related health issues (Svemin, 2022a). Health issues for workers in Bolivian mines described in grey literature are lack of oxygen, rock dust, heat in the tunnels, inhumane shift durations and a lack of health insurance (Cultural Survival, 2010). In addition, accidents, child labour and poisonous substances such as mercury, carbon monoxide and cyanide are described (Vince, 2012).

3.1.3 Economic issues

The peak of virgin silver production is expected around the beginning of 2030. Around the same time, or earlier, alternatives like gold, copper, or nickel will become scarce, so replacing silver will be a challenge. By 2170, the end of pure silver mines is projected. After that, it will only be available as a co-product with copper and zinc. By 2300, almost no supply is expected anymore. On average, the silver price has risen 30-40% from 2015-2020 (Despeisse, 2021). This implies an urgent need for greater efficiency and recycling in the future. With the resulting rising raw material prices, recycling rates will increase, leading to improvements in recycling efficiency (Sverdrup et al., 2014). This has already been seen today, as the recycling rate is rising every year (e.g. 7% in 2020; The Silver Institute & Metals Focus, 2022). After 2100, most silver will be sourced from urban mines or recycling (Sverdrup et al., 2014). An average of 630g of silver per ton of solar PV modules can be recovered (Dias et al., 2016).

3.2 Silicon metal

Silicon is the second most abundant material in Earth's crust (Latunussa et al., 2020). It is found in quartz, which is mined to derive silica sand and then purified into silicon metal (Figure *2*) (Heidari & Anctil, 2022). Two grades of high purity silicon metal exist. Metallurgical grade silicon (MG-Si) is used in the chemical and aluminium industry, while polysilicon is higher in purity and is a widely used as a semiconductor in solar cells and electronics (Latunussa et al., 2020). 95% of PV modules produced today are crystalline silicon based because of their high efficiency, low cost, and long lifespan (Benda & Černá, 2020).

Figure 2: Silicon in its metallic form

3.2.1 Environmental issues

The production of MG-Si is energy intensive (Latunussa et al., 2020). The polysilicon used in PV cells requires extra purification steps, further increasing the energy consumption of production. Scarcity of high-quality quartz deposits could lead to the use of lower quality quartz, which again would require more purification and more energy use. China already plans to increase their use of domestic low-quality quartz to meet growing silicon demand (Heidari & Anctil, 2022).

China is the largest producer of high purity silicon and, especially in the Xinjiang region where most is produced, coal is the primary energy source, resulting in a high associated carbon footprint (IEA, 2022; Latunussa et al., 2020). In contrast, most silicon metal production plants in Europe run on hydropower and are part of the EU Emissions Trading System which sets limits on greenhouse gas emissions (Latunussa et al., 2020; Project Blue, 2022).

Besides the environmental impacts of energy consumption, excessive silica sand mining in rivers and oceans (usually associated with illegal mining) can change erosion patterns, reduce the fertility of surrounding soils, and increase water pH and turbidity (Heidari & Anctil, 2022).

As an alternative to primary silicon metal, using recycled polysilicon from waste PV modules or electronics could reduce the environmental impact of a PV module by 58% (Klugmann-Radziemska & Kuczyńska-Łażewska, 2020).

3.2.2 Economic issues

Despite the abundance of silicon, silicon metal is listed as a critical raw material by the European Union because of its economic importance and supply risk (European Commission, 2020). Although the amount of polysilicon per PV cell is decreasing due to efficiency improvements, the increase in demand for solar energy will increase the net demand for polysilicon (Bartie et al., 2021). Polysilicon is also crucial in wind turbine generators, lithium-ion batteries, and modern electronic devices, amplifying the need for the material (Latunussa et al., 2020). Furthermore, there are currently no substitutes for silicon metal that match its performance and cost, and the current recycling rate is 0% (European Commission, 2020; Latunussa et al., 2020).

China is the main global producer of silicon metal (66%), followed by the United States (8%), Norway (6%), and France (4%) (European Commission, 2020). While on the raw material level, Europe only sources 11% of its silicon metal from China (European Commission, 2020), it is 89% reliant on China for crystalline silicon solar cells, meaning its reliance on Chinese silicon is much higher when considering the silicon already embedded in components (Bobba et al., 2020). This dependence on China and the fact that Europe is 63% reliant on imports for silicon creates a supply risk. To address this issue, more local silicon suppliers should be used such as Norway (who already meets 30% of European silicon demand), France, Germany, and Spain (European Commission, 2020). Bobba et al. (2020) also suggests that the EU acquire silicon metal from the USA and Brazil.

3.2.3 Social Issues

For the high purity silicon metal used in PV modules (polysilicon), China produces 79% of the world’s supply, with 42% coming from the Xinjiang region (IEA, 2022). In this region, investigations have revealed that Uyghur Muslims are subject to forced labour conditions. A study by Murphy & Elimä (2021) determined that the world's largest metallurgical grade silicon producer (Xinjiang Hoshine Silicon Industry) and four of the largest polysilicon producers (Daqo New Energy Corp, GCL-Poly, TBEA/Xinte, and East Hope) use or are associated with these forced labour practices. The authors go on to map the downstream PV component manufacturers that therefore have forced labour in their supply chain, some directly participating in it themselves. An overview of their findings showing how Xinjiang forced labour permeates the silicon and solar PV supply chain can be seen in Figure 3 with more details and a further analysis of potentially impacted suppliers available in their report. In response, the United States has banned all products from the Xinjiang region, including products containing components from this region (Uyghur Forced Labour Prevention Act, 2021). Similarly, the European Union plans to ban all products that are produced with forced labour, and while it does not explicitly mention Xinjiang, the ban is thought to be directed at China’s human rights violations (Pronczuk, 2022).

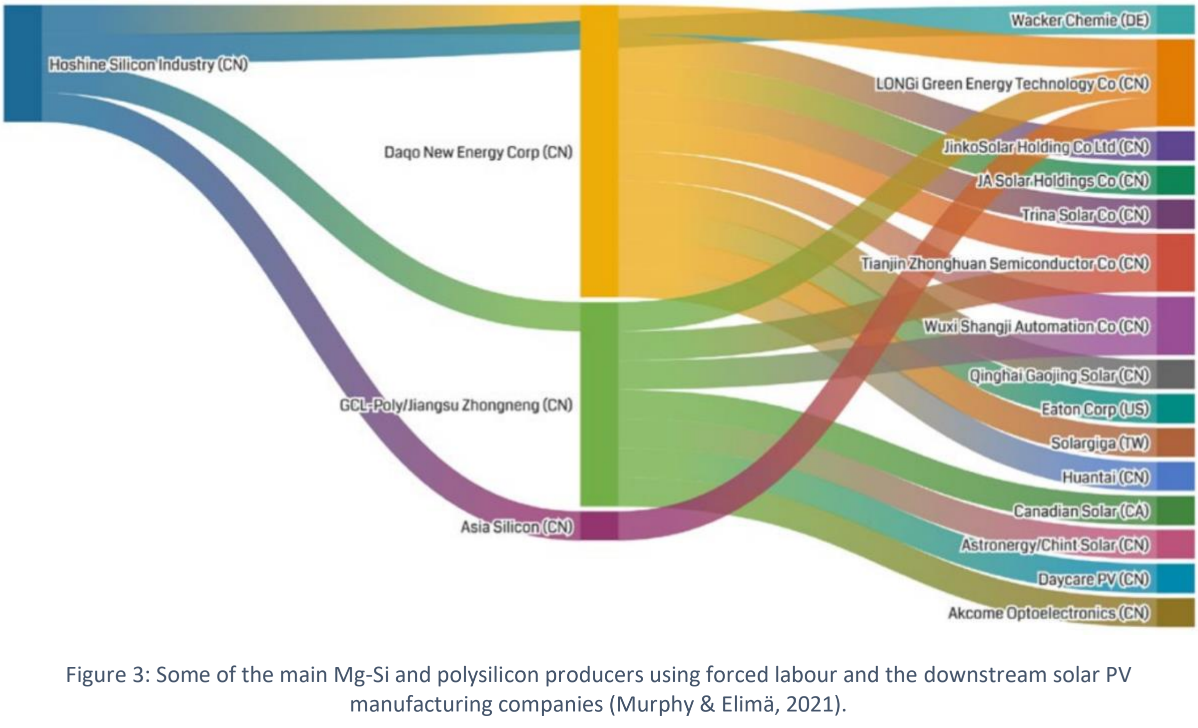


Figure 3: Some of the main Mg-Si and polysilicon producers using forced labour and the downstream solar PV manufacturing companies (Murphy & Elimä, 2021).

Despite being the largest producer of silicon metal, China does not actually have high purity quartz deposits and is greatly reliant on imports from Cambodia, Australia, Malaysia, and Pakistan for the high-quality silica sands. Possible illegal mines have been reported in Cambodia and only 14% of China’s imported silica sand is traceable through documented trade. These illegal mines can have detrimental social and environmental impacts due to the lack of legislation (Heidari & Anctil, 2022).

3.2.4 Conclusion

In order to minimise environmental impact, increase supply security, and prevent forced labour in the supply chain, polysilicon from China should be avoided. Sourcing polysilicon from countries such as Norway and reusing and recycling polysilicon are important strategies for achieving this goal.

3.3 Copper

Approximately half the mining of all copper is controlled by a mere 10 companies, and a large part of global mining happens in Chile (Blengini et al., 2020; Folke et al., 2019). Though the EU's demand for the raw material is largely satisfied by EU sources, global processing happens mainly in China (Blengini et al., 2020). Using pyrometallurgy, the mineral is extracted with thermal treatment (Figure 4) (Dong et al., 2020). An upcoming alternative is hydrometallurgy, which uses aqueous solutions and is more energy intensive (Harmsen et al., 2013). However, with ore grade declining, this latter method is gaining traction (Dong et al., 2020). An academic consensus exists that secondary copper extraction is most beneficial on the environmental and social front, while also offering economic opportunities on the long term. This method uses pyro- or hydrometallurgy but avoids mining and beneficiation, which utilise 85% of all energy in extraction (Akbari-Kasgari et al., 2022; Harmsen et al., 2013). Still, recycling will not satisfy the projected increases in copper demand soon, maintaining primary production's importance in the coming decades (Fuentes et al., 2021).

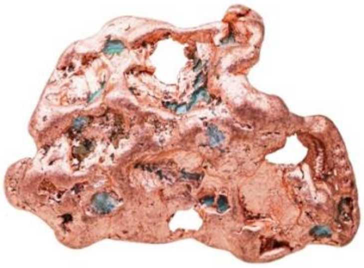


Figure 4: Copper in its metallic form

3.3.1 Environmental issues

Copper production requires large amounts of water and releases a lot of air pollutants (Akbari-Kasgari et al., 2022). Additionally, mining sites are surrounded by biodiversity loss and worsening water quality (Dong et al., 2020). In the major mining country of Chile, 25% of the energy used in the copper sector comes from renewables. The authors further estimated that fully using solar instead of fossil-based electricity in copper production could reduce its contribution to global warming by 60% (pyro) or 75% (hydro) in Chile.

Apart from greenhouse gas emissions, however, copper production results in impacts like local heavy metal and sulphur dioxide emissions to air, and pollution of freshwater with heavy metals and phosphorous. Still, with ore grades declining, tailings will also increase, and their toxicity has been linked to increases in the mortality of marine life (Moreno-Leiva et al., 2020).

3.3.2 Social issues

Newhook et al. (2003) suggest that margins between airborne concentrations of copper and tumorigenic potency is rather small near copper smelters. The authors conclude that a high risk exists to human health, from exposure to emissions from the smelters, compared to other substances. Moreover, Patra et al. (2016) state that high contents of copper could cause Wilson's disease, while Moya et al. (2019) identify 'high concentrations' of the mineral in street dust close to mines. Moreover, copper mining can have further negative impacts on communities. The La Oroya project in Peru was linked to substantial arsenic, cadmium and lead contamination. The Mexican Buenavista mine caused sulphuric acid to contaminate the Sonora River, reducing drinking water quality for 20,000 locals. Lastly, a Zambian mine has been the target of legal action by residents, who blame its operations for polluting drinking water (Milios, 2022). Copper's high human toxicity potential in combination with future increased tailings, potentially affect human health through leaching into runoff waters. This could be prevented or reduced by increased recycling of tailings (Dong et al., 2020).

3.3.3 Economic issues

Copper is of economic importance for the energy transition, though the material has a relatively low supply risk. Copper occurs in high densities in specific locations; however, the mineral is vulnerable to so-called disruption risks. Consequently, it is recommended that supply chains have backup suppliers (Akbari-Kasgari et al., 2022). Of total copper use, approximately 17% comes from secondary sources (Blengini et al., 2020). Contrarily, open pit mining accounts for 80% of global primary production (Harmsen et al., 2013).

Modelling static depletion, the economically extractable copper amount suffices for 32 years. Though, if the reserve base and later resource may be exploited, this estimate increases to over 64 and 100 years, respectively (Alonso et al., 2007). Under dynamic depletion, including technological progress and consumption trends, copper depletion is estimated in 20-50 years. Alonso et al. (2007) conclude that copper depletion is not imminent, though its disruption risk is substantially bigger than for other important metals. Also, tapping into the reserve base and resource will require more energy per kilogram of minerals mined and therefore significantly decrease the energy return on investment of renewable energy technologies (Harmsen et al., 2013).

3.4 Antimony

Antimony (Sb) exists in various chemical forms (Figure 5). It has an ancient history tracing back to 3100BC, where it was utilized by the Egyptians in its dark form (Sb_2S_3) for cosmetic purposes (Dupont et al., 2016). Today, antimony oxide (Sb_2O_3) takes up the majority of the world's antimony production, and is used as a flame retardant for plastics and textiles (Dupont et al., 2016). The next most common use for antimony is for hardening lead alloys such as the lead electrodes in lead-acid (LA) batteries (Dupont et al., 2016). In the PV industry, antimony is used in the solar panel glass to improve performance upon exposure to ultraviolet radiation or sunlight.

Antimony is naturally present in the Earth's crust in small amounts, and is released into the environment through tectonic or anthropogenic activities, and forest fires (Roper, 1992).

Because antimony is very brittle, it is often alloyed with other metals such as zinc and lead to increase its strength and durability (Roper, 1992).

Demand for antimony is forecasted to increase, as the energy transition will require more PV glass, and more battery storage options to compensate for the intermittency of renewable technologies.

Figure 5: Antimony in its metallic form

However, antimony presents a scarcity risk. Due to the low availability of antimony in the Earth's crust (o.2 ppm), reserves are quickly depleting. Currently, antimony reserves are estimated at around 1,800,000 t, which, at current extraction rates, may only last for a decade more (Dupont et al., 2016). Considering bioavailability alone, the gap between supply and demand is expected to exceed 10% in the coming years, making antimony supply far more critical than rare-earth elements (Dupont et al., 2016).

Importing countries also face a supply risk. The world's largest reserves of antimony are found in China, Russia, and Bolivia, yet China is responsible for producing 74% of the world's antimony in 2020 (European Commission et al., 2020; Roper, 1992). In the EU, antimony sources are 100% imported, coming mainly from Turkey (62%), Bolivia (20%) and Guatemala (7%) (European Commission et al., 2020). Regardless, due to the Belt and Road Initiative, China exerts diplomatic and technological influence over these producing countries as well. As a result of the Chinese monopoly over the resource, market prices for antimony are increasing, due to artificial pricing and export restrictions (Brink et al., 2022).

3.4.1 Health risks

Continuous exposure to antimony at 2 mg/m3 can irritate the eyes and skin, and cause lung problems (pneumoconiosis) and heart irregularities. Antimony toxicity typically occurs due to occupational exposure. In China, dangerous concentration levels of antimony were found in the land surrounding the mining and processing factories of antimony (up to 143.7mgkg^{-1}, which vastly exceed the tolerable concentration 5mgkg^{-1}). These figures raise doubts as to the occupational safety of the workers. (He et al., 2012)

3.4.2 Environmental issues

The mining of antimony releases potentially toxic elements (PTEs) such as Sb and its compounds, which are listed as pollutants of priority interest by the EU (Zhou & Hursthouse, 2019). These toxic substances leach into soils, sediments, and aquatic environments, causing harm to ecosystems and potentially to public health via bioaccumulation in the food chain (Bolan et al., 2022). Metalloid contamination also negatively impacts soil biodiversity and plant growth (Steinhauser et al., 2009). Lastly, the waste produced by mining is not only polluting, but also occupies large areas of land (Zhou & Hursthouse, 2019).

3.4.3 Recycling

Most of the antimony used in LA batteries is recycled (Roper, 1992). Little information concerning the disposal of antimony and its compounds was found in the literature. Wastes from mining and smelting are generally landfilled, which is evident from the high concentrations of antimony in the surrounding land and water systems (He et al., 2012; Roper, 1992).

There is much untapped potential for the recycling of antimony. Secondary sources of antimony from industrial residues (e.g. mine tailings, slag, and manufacturing scrap) could potentially replace a large portion of primary production, therefore subsiding the scarcity problem (Dupont et al., 2016).

3.5 Tin

In 2020, around 40% of Tin production came from Myanmar, Thailand, Malaysia and Indonesia, the whole region is known as the SE Asian tin belt (Lehmann, 2021). Tin has been used as a lead substitute in photovoltaic applications as it is considered a non-toxic material in comparison with lead (Mahajan et al., 2021). However, tin is obtained from casserite, which is considered to be a conflict material (Figure 6). Conflict minerals are those that are mined in places under armed conflicts and human rights abuse. Tin for example, has been involved in the situation in Democratic Republic of Congo (DRC), where the profits from selling the mineral are used to purchase weapons mainly for rebel groups and local militias, who are in control of a majority of the mines (Yuthas & Sarkar, 2011).

In general, 99% of tin production comes from primary deposits (ore deposits) or indirectly (placer deposits), a smaller quantity comes as a by-product (Lehmann, 2021). However, the mechanical methods to produce and extract tin are simple; therefore, part of the global production comes from artisanal and small-scale mining (ASM), with a share of about 40% of the global tin production (Vasters & Franken, 2020). This represents informal jobs and illegal practices as will be introduced below.

Figure 6: Tin in its metallic form

3.5.1 Environmental issues

Environmental impacts can be classified under three indicators: biodiversity impacts, sea use, and land use. According to Vasters & Franken (2020), sea use is driven by offshore extraction. In 2010 around 20% of the tin production came from suction dredging or excavation of the seabed, disturbing the sea floor. The formal industrial sector is allowed to mine outside a 2km limit to the coastline; however, ASM activities have established their mining activities within the 2km limit, affecting a bigger area. Besides, offshore extraction also damages areas not directly affected by mining. This is due to the presence of fine soil particles that when settling slowly can damage flora and fauna at some distance from the extraction point, affecting marine biodiversity. In terms of land use, in Southeast Asia, illegal post-mining activities from ASM groups are a problem as it takes place in previously recuperated land, which is not recovered again (Vasters & Franken, 2020).

3.5.2 Social issues

When looking at the social aspects, the effects in terms of occupational safety and health can be measured. Throughout history, there have been some tin mines that have been closed or abandoned. These places have become breeding areas for mosquitoes, increasing or being the source of malaria cases in the community. Singkep island, where mining activities were abandoned, is an example of this (Syahrir et al., 2020). In terms of occupational safety, the working conditions for the ASM activities are an issue. There are records of collapsed underground mining tunnels, and the mining in unconsolidated rocks has led to accidents not only for miners but also for residents (Vasters & Franken, 2020).

3.5.3 Economic issues

Job creation and scarcity can be used to measure economic impacts. Going back to the Singkep case, before the mining activities were abandoned, tin mining contributed to between 65% and 90% of the local economy before 1993, however it seemed to produce job dependency. When job dependency happens, independent communities are not resilient if the activity closes, thus they contribute to unsustainable development (Syahrir et al., 2020). From a different perspective, AMS activities create economic opportunities in less developed and rural areas, especially in Southeast Asia (Indonesia, Myanmar), Central Africa (Rwanda, Burundi, Democratic Republic of Congo), Brazil and Bolivia. These activities are not illegal but are not formal (Vasters & Franken, 2020). In terms of scarcity, according to a report published in 2020 by the International Tin Association, the current demand for tin can be supported for 50 more years; however, this varies per region. There is a possibility of discovering new sources for future demand; nevertheless, higher prices are expected and there is a need of more efficient extraction technologies. Moreover, the number of resources and reserves in some areas is unknown given the high amount of artisanal and small-scale mining, as well as a lack of transparency from private tin industries (International Tin Association, 2020).

Tin is catalogued as a conflict mineral. The best supplier would probably be within the EU as there is a new regulation that requires the import of conflict materials from responsible sources. The requirement started applying in January 2021 (European Commission, 2021).

4 Component level

The next phase of research involved assessing how the raw material issues translate to the manufacturing of PV module components. In coordination with the commissioner, it was decided to focus on the solar cells, glass, and interconnection metal (wiring).

The general sustainability issues related to component production were examined, together with best practices and end-of-life options. A look at European suppliers can serve as a best practice example because of the strict regulations and relatively high transparency. From there, the derived criteria can also be used to evaluate overseas component manufacturers.

4.1 Solar cells

4.1.1 Market analysis and current practices

Solar cells are the core component of PV modules as they are responsible for converting sunlight into electricity. There are various types of solar cells. Crystalline silicon (c-Si) solar cells account for 95% of the market share, with thin-film solar cells accounting for the remaining 5%. Of the c-Si solar cells, passivated emitter, and rear cells (PERC) cells are the most commonly used, representing 85% of the market in 2021. However, this is expected to decrease to 70% by 2032, as the market share of Si-heterojunction (SHJ) cells rises to 20%. The market share of back contact cells will only slightly increase, rising to 5% in 2032, while BSF cells are already being discontinued (Fischer et al., 2022).

A c-Si solar cell is made of a silicon wafer and metallisation pastes, which contain silver and aluminium (Fischer et al., 2022). Although solar cells only account for about 6% of the PV module's total mass (Mulazzani et al., 2022), they are responsible for most of the environmental impact (Jia et al., 2021; Müller et al., 2021). According to Müller et al. (2021), a PERC solar cell accounts for about 70% of a PV module's impact on climate change, mainly due to the energy intensive process of polysilicon production. Whether 50, 60, or 72 solar cells are used in a PV module have little impact on the module's environmental performance (Jia et al., 2021).

Since most of the environmental impact of a solar cell is attributed to the silicon wafer (Jia et al., 2021; Müller et al., 2021), which all c-Si solar cells require, there is thought to be little difference between the upstream environmental impacts of various c-Si solar cell types (Dullweber, 2022). Nevertheless, Jia et al. (2021) found that bifacial PERC modules have a lower environmental impact than mono-facial PERC modules, mainly due to their ability to produce 23% more energy throughout their lifespan. In addition, bifacial cells use significantly less aluminium in their metallisation since the back side uses 75% less aluminium compared to mono-facial cells. Furthermore, both mono-facial and bifacial PERC cells use less silver compared to SHJ cells. In general, trends show that the amount of polysilicon, silver, and aluminium in solar cells is decreasing over time, in order to minimise material use and reduce costs (Fischer et al., 2022).

China produces nearly 80% of the world's polysilicon, 97% of the world's silicon wafers, and around 80% of the world's solar cells (IEA, 2022). A remaining 18% of solar cells are produced in Southeast Asia and Korea, although according to IEA (2022) many of these manufacturing plants are also owned by Chinese manufacturers in an attempt to avoid American import tariffs and bans. Only 2% of solar cell production occurs outside of these three regions. Although the shift of PV supply chains to China since 2010 has helped make PV modules more affordable and therefore aided in the energy transition, the resulting high reliance on a single country and even a small selection of production plants has created a supply risk (IEA, 2022). The supply chain is vulnerable to for example domestic policy changes, trade restrictions, or plant failures, and IEA (2022) therefore suggests diversifying the PV supply chain by expanding manufacturing in other countries. Increasing the manufacturing of solar cells and PV modules in countries with a more renewable electricity mix would also help reduce the environmental impact of PV supply chains (IEA, 2022).

4.1.2 Best practices

After analysing the sustainability aspects of the raw materials, it was found that if the materials come from European sources, the sustainability issues could decrease as the extraction activities are more regulated. Moreover, not only the material level matters; in fact, while researching the component level it was found that "SolarPower Europe", an association that serves as a link between policymakers and the solar energy value chain, propounded a similar approach by doing a benchmark to introduce the best PV practices in Europe and position the European sector as a sustainability leader (Stephan Braig et al., 2021).

One of the biggest issues in the production of solar cells is the energy required to produce them. This input of the electricity is the main source of GHG emissions, especially if the cells are made from polysilicon. Some of the best practices in the industry to reduce the electricity consumption are closed loop operations, optimised processes, and energy reuse (Stephan Braig et al., 2021)

Among successful examples in the reduction of electricity consumption is REC Solar Norway who, with the introduction of a specific purification method, has been able to manufacture polysilicon with a 75% electricity reduction in the cell production and reduced material wastage (Osborne, 2021). Similarly, WACKER in Norway, has been able to reduce its energy consumption in the production of polysilicon by 29% by improving the performance of its reactors (Wacker, 2022). However, Wacker is potentially linked to forced labour through its polysilicon supply chain (Murphy & Elimä, 2021b).

Other approaches have been to look for polysilicon alternatives, such as Upgraded Metallurgical Grade (UMG) silicon. In an LCA study, a reduction of 33% in the cumulative energy demand was shown when using UMG instead of polysilicon (Méndez et al., 2021). Furthermore, Elkem Solar Silicon shows a potential reduction of 70% in energy consumption (Forniés et al., 2016) in comparison with polysilicon.

Using energy from renewable sources reduces the footprint of the manufacturing of the cells. For instance, Norwegian Crystals produces low carbon footprint silicon due to the use of hydro energy and its access to natural cooling water; furthermore, its materials claim to be sourced from conflict free regions (Norwegian crystals, 2022). Comparably, Norsun, based in Norway, uses hydropower and among its processes has reduced the wafer thickness of the cell and has switched from a slurry-based to a diamond-based wire to decrease the amount of silicon that is lost in the sawing of the wafers (Stephan Braig et al., 2021).

To increase the solar cell efficiency, some research and development has been done in terms of new technology. Heterojunction cell technology (HJT) on silicon solar cells, combines thin film and crystalline cell technologies and has been shown to increase solar cell efficiency by around 20%, decreasing the temperatures needed in the production process, and anticipating reductions in PV energy generation costs as well (Bätzner et al., 2011). The way it works is that an amorphous thin-film silicon layer captures the sunlight before the crystalline layer; the crystalline layer transforms it into electricity while the last thin-film captures any photon that has surpassed the first layers (Kaneka, 2022). PERC is another technology with high-efficiency and the current most dominant cell technology. PERC has reduced the surface recombination and increased the surface reflection, which has improved the light capture near the surface and optimized the electrons capture (Aleo, 2022; Green, 2015).

Overall, besides the hotspots dealing with the energy consumption in the production of the cells, several improvements have been made, mainly by European companies, while technologies keep on being developed to increase the efficiency of the cells.

4.1.3 End-of-life

Acknowledging the hierarchy of waste management as laid out by Gertsakis & Lewis (2003), it would be most appropriate to reuse complete solar cells. Though Lunardi et al. (2018a) suggest that the materials have the potential to be reused, the authors also find that this has some drawbacks. Specifically, the reuse of full cells would come with reduced efficiencies and only prolong lifetime by approximately 15 years. With the current lack of recycling facilities specialised in PV modules or solar cells, the materials would thus still be disposed of (Weckend et al., 2016). However, Weckend et al. (2016) also argue that by 2030 approximately 30,000 tons of just silicon could be recycled on an annual basis. Estimated to be enough for the production of 45 million new PV modules worth 380 million USD, the authors suggest that cell recycling will become more abundant and specialised in the coming years. Lunardi et al. (2018) also argue that through (the combination of) different recycling methods, successful recycling of materials is already possible. Specifically, Calì et al. (2022) suggests that through a chemical recycling process, crystalline silicon cells can be separated into silicon plates and copper. The latter material can be 100% recycled and does not need much further processing before it is useful again. The silicon requires an additional recycling step that turns it into silicon powder, which can be used in other technologies or as a base material for new PV cell manufacturing. With the recycling of lithium and copper from end-of-life modules, a number of harmful production steps can be avoided. Secondary materials do not need conventional mining, which was found to be associated to many environmentally and socially unsustainable practices (Akbari-Kasgari et al., 2022; Dong et al., 2020). Besides, using secondary lithium and copper does not further deplete the resource base of each material, and avoids the global supply chains that have a substantial risk of disruption (Akbari-Kasgari et al., 2022; European Commission, 2020). However, the present status is that used copper comes from secondary sources 17% of the time, while silicon is merely recycled in aluminium alloys (Blengini et al., 2020; Gregoir, 2022). No pure silicon is currently being recovered in Europe, though there are European initiatives focused on establishing recycling facilities for this material from PV modules (European Commission, 2020). Particularly, a number of PV module or cell focused recycling initiatives are piloting in Europe (Table 1). With this focus on solar cell recycling and secondary materials, cell manufacturers have the potential to establish a more European and less environmentally impactful supply chain.

Table 1: PV module recycling plants, with special focus on silicon for ReSiTec and SolarWorld

Plant	Location
Geltz Umwelt-Technologie (Geltz Umwelt-Technologie GmbH, 2023)	Germany
ReSiTec (ReSiTec, 2023)	Norway
Soren (Soren, 2023)	France
SolarWorld/Deutsche Solar	Germany
First Solar	Germany
Veolia (UpToUs, 2023)	France

4.2 Glass

4.2.1 Introduction

Solar glass is used in photovoltaic modules for protection against environmental factors such as water and dirt. It can also enhance performance thanks to the deposition of anti-reflection (AR) coatings, and it can be used as a substrate for thin film modules. Glass offers desirable properties for solar energy, because it is a good transmitter with high reflectance that does not corrode easily. However, it is also breakable and heavy. This imposes restrictions in the design of PV modules. In current photovoltaic module designs, glass is the largest component by mass, accounting for up to 80% of a module’s weight (Mulazzani et al., 2022). In terms of cost, glass contributes to 10-25% of the total costs for PV module manufacturing (Allsopp et al., 2020).

4.2.2 Market Analysis

Up until ten years ago, Western companies dominated the flat glass market, which is the segment which produces solar glass for PV modules. Today, however, the top 4 producers of solar glass (in terms of production volume) come from Mainland China (Table 2). For most glass companies, the solar glass segment is only a very small part of the product lines since global demand is still relatively low (Green Rhino Energy, 2016). This, however, could change in the near future, given the excellent prospects for this commodity.

Indeed, the global flat glass market size was valued at USD 273.43 billion in 2021 and is expected to grow at a compound annual growth rate of 4.3% from 2022 to 2030 (Grand View Research, 2020). The rising number of solar energy installations, driven by governmental regulations and rising environmental concerns, is propelling the solar glass market growth.

There is a supply and demand imbalance for the global flat glass market. While China produces most of the flat glass, Europe and the Middle East are net importers, despite the relative high transport costs for glass. This imbalance derives in part from higher labour and energy costs in Europe compared to China (Green Rhino Energy, 2016).

Table 2: Top Four Flat Glass Suppliers Worldwide

Name	Country	Description
Xinyi Solar Holdings Ltd.	China	An investment holding company principally engaged in the manufacturing and sale of solar glass.
IRICO Group New Energy Co., Ltd.	China	A holding subsidiary of IRICO Group Co., Ltd., specialises in the research and development of new energy photovoltaic glass.
Flat Glass Group Co., Ltd.	China	Principally involved in the research, development, manufacturing and sales of glass products, including the mining and sales of glass quartz mines. The company's main products include photovoltaic glass.
Qingdao Jinxin Glass Co., Ltd.	China	Main products include solar glass.

Although the Chinese market is very competitive, we predict that a European supply chain could be possible. Firstly, the transportation costs for glass are very high, therefore providing an incentive for businesses to source their glass needs more locally. Additionally, in a post-pandemic world, European politicians are increasingly motivated to establish independence from foreign countries for vital goods such as energy. Finally, a European supply chain would fit within the Paris Agreement goals, as a European PV production would reduce CO2-eq emission by 40% compared to Chinese production (Müller et al., 2021). These factors open up a market opportunity for a European solar energy supply chain.

4.2.3 Current practices

In a PV module, typically the substrate glass is made of standard glass, while the superstate needs to offer low reflection, high transmissivity, and high strength. Antimony is often used as an absorber material in photovoltaic glass. Thin films of antimony sulphide Sb_2S_3 are chemically deposited onto glass to create more favourable optical band gaps (Messina et al., 2007). Although antimony enhances the performance of PV modules in the use phase of their life cycle, the metalloid becomes problematic in the end-of-life phase. As antimony adheres to the glass surface, it causes impurities which make the glass impossible to recycle (personal communication from BS).

The melting and fining of glass is energy-intensive, and the current float glass industries use mainly natural gas as a heat source, leading to high carbon emissions (EIA, 2013). Additionally, glass manufacturing also requires raw materials (soda, quicklime, silica sand) whose mining also causes environmental impacts. The use of recycled glass cullet not only requires lower melting temperatures, but also avoids further raw material extraction (UNCTCN, n.d.). This is why it is important to recycle glass as much as possible.

There already are some suppliers, such as AGC, which provide antimony-free glass. However, for optimum PV efficiency, other absorber materials should be added onto the glass substrate, whilst still allowing recycling.

4.2.4 Best practices

A promising option for low-cost absorber layers is the quaternary compound Cu_2ZnSnS_4 (Copper zinc tin sulphite; CZTS). Research shows it provides a low-cost, environmentally benign and stable photovoltaic material (Yan et al., 2018). Its constituents are non-toxic and abundant in nature, and it therefore is a better alternative than the more popular CdTe or SIGS, or compounds containing antimony. The band gap values reported for CZTS fall within the optimum range for a single junction terrestrial solar cell (Scragg et al., 2008).

A market analysis has shown that CZTS products could easily be scaled to terawatt levels to match the growing PV demand. CZTS also has a good low-light performance and can be configured with low weight and high flexibility. The manufacturing cost of CZTS at a production volume of 1 GW per year is between \$41–52 per m^2 (Wang et al., 2021). The typical configuration of solar cells with CZTS absorber layers is shown below (Figure 7).

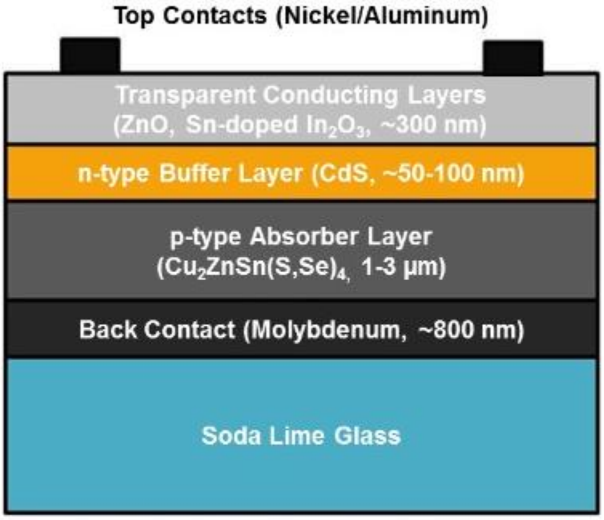


Figure 7: Typical architecture of a CZTS-based solar cell (McClary et al., 2016.)

The main challenge for industrialization and large-scale manufacturing of this material lies in its chemical complexity. Reaching a pure composition is difficult, and crystal defects can arise easily (McClary et al., 2016). Research to prevent such defects is ongoing.

4.3 Interconnection metal

4.3.1 Market analysis and current practices

There are two types of wires used in PV panels: tabbing and bus bar wires. Tabbing wires connect the single cells in the PV module. On the other hand, the bus bar wires are thicker and connect the rows of the tabbing wires. They are usually made from silver or copper as conductive materials (Tao et al., 2020). Cost-wise, silver has a share of 10-30% in the total costs of a PV module (Copprint, 2022). The wires are the most critical for the cell to work, and, if made from silver, the next most expensive component after the silicon. 30% of the global silver production is used for PV modules, and it is projected to become a limiting material for the growing industry (Dullweber, 2022). A reduction of material needed is expected within the next 10 years, but innovation is necessary. For that, a good cooperation between suppliers and manufacturers is essential (Despeisse, 2021). The International Technology Roadmap for Photovoltaic (ITRPV) highly recommends silver to be replaced (e.g. with copper or aluminium) or extremely reduced (Sinha & de Wild-Scholten, 2015). A reduction could be approached with an optimized structure of the electrodes or the printing (Jia et al., 2020; M. Lunardi et al., 2018) .

Silver-based metallisation paste is conductive and forms the metal grid in the front of the module, on an aluminium panel. From a life cycle perspective, it has been identified as a strong contributor to human toxicity, freshwater ecotoxicity and abiotic depletion (as it is a rare metal). Copper causes half of life cycle resource depletion impacts compared to silver (front and backside wiring; Sinha & de Wild-Scholten, 2015). A different study saw the wires as a lower contributor to the climate change impact category (Müller et al., 2021).

A 19% cost reduction potential of copper is estimated compared to silver because of the lower raw material price. Copper is 800x more abundant than silver in the earth crust and has a lower carbon footprint (Rudolph et al., 2022). Copper metallisation paste for bus bar printing is technologically challenging because copper defects the silicon cells in its proximity. That reduces the cell efficiency (Dullweber, 2022). Copprint claims to have solved that problem with a technology that has comparable properties and efficiency (23%) (Copprint, 2022; Rudolph et al., 2022). Alternatively, aluminium is more abundant and cheaper than silver and the development of aluminium wiring is in progress (Dullweber, 2022). Tin can be a coating for the copper wires (International Tin Association, 2022).

Backcontact (BC) cells are specially structured cells, where positive and negative external contact pads are on the back surface of the module. This also increases the PV module efficiency through lower series resistance (Fthenakis, 2018; van Kerschaver & Beaucarne, 2006)

A conductive back sheet is an alternative to the wires from metal paste: It covers the whole backside of the module and is usually made from copper (electrically conductive adhesive) (Broek et al., 2015). Around 300g/m^2 are needed for the back sheet. As an innovation, it could be thinned, but then there would be a lower current, so a construction with half cells would be necessary (Endurans, 2022a).

Currently, BS uses the Sunpower IBC (interdigitated back contact) copper back sheet, which is silver-covered (Neuhaus & Adolf, 2008). Considering material scarcity and environmental impacts, a preference of copper over silver is recommended, with the decision to make between conventional wires or a back sheet design.

4.3.2 Industry best practises

SveMin (Swedish mining union): Mines in Sweden take up 0.04% of Sweden's total area, while supplying 18% of silver and 11% of copper in the EU. The Swedish mines, mineral and metal producers have formed SveMin, an association for networking and shared guidelines. The high sustainability standards can serve as a best practice example for an ethical supply of these metals.

Regarding health and safety, the level of automation is increased. Safety exercises are performed on a regular basis. Positions of humans and machines are tracked digitally. These measures result in an accident rate close to zero.

Further, future strategy roadmaps to enhance and preserve biodiversity and for a higher value chain traceability are developed. Other initiatives are worker's skill development, fossil fuel elimination, research to increase circularity, permits with sustainability considerations, and a higher transparency (Svemin, 2022d, 2022c).

Endurans^{TM} Solar: Produces back-contact PV modules with a conductive backsheet (already on the market for 5 years; Endurans, 2022b). The producer recommends a combination with the Zebra IBC cells from the ISC Konstanz. The production is in the United States (Endurans Solar, 2022).

Copprint: Offers biodegradable copper printing for solar PV wiring. Implementation tests are already running with some partners (Copprint, 2022). Problems are known with copper diffusing into silicon parts, but in this design, it does not happen (Rudolph et al., 2022).

Lightyear: For the PV modules on their vehicles, Lightyear uses backcontact cells and conductive back sheets. The surface is better used, which improves the performance in partial shade conditions (Lightyear, 2022).

4.3.3 End of life

A 100% recovery of silver from solar PV modules in end-of-life is feasible. The recycling of individual components lowers the environmental impact compared to conventional disposal without modularity (Lunardi et al., 2018). What happens end-of life for the recovery of copper metallisation is still unresolved (Copprint, 2022).

5 Supplier level

As part of the deliverables for the commissioner, we developed a multi-criteria decision matrix tool in an Excel file that has the intention to help Biosphere Solar to evaluate potential suppliers for their components. All the different steps to follow can be found in the file "*Supplier level tool - Biosphere Solar*". In a nutshell, the steps performed are stated below.

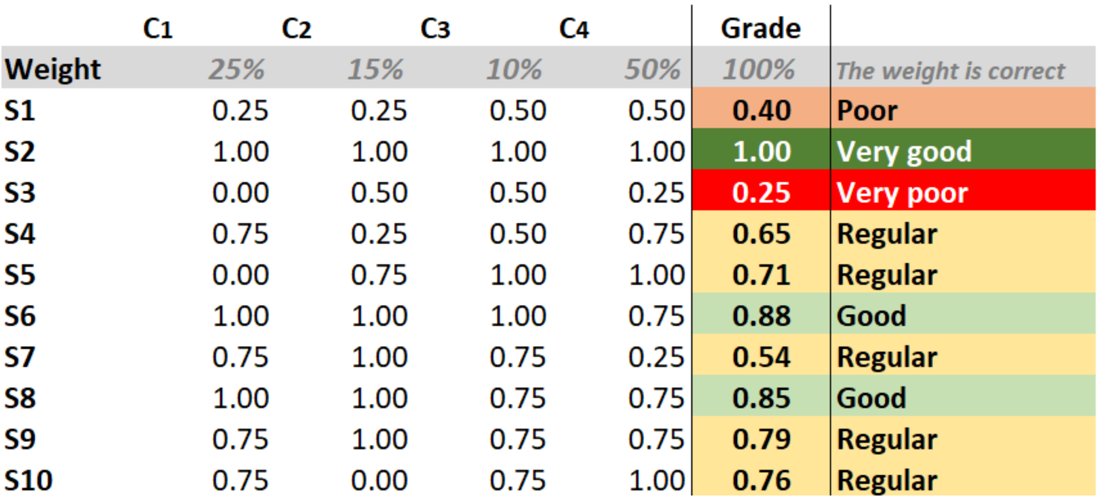
Based on the findings of the material and component level research, a number of main critical aspects to consider when establishing a supply chain emerged. These aspects were grouped under four criteria: C1 - Location, C2 - Choice and efficiency of materials and/or components, C3 - Energy use and C4 - Occupational health and safety. Some aspects could be considered part of more than one criterion but were grouped only under the one it relates most to. This ensured the matrix stayed mutually exclusive.

Taking into account the critical aspects identified in the literature review, a set of questions was developed for Biosphere Solar to reflect on and grade for each of the possible suppliers. For example, for C3 - Energy use, the questions mainly inquire if the possible supplier uses renewable energy, if within its operations there are strategies to increase energy efficiency, and if there is published data around the real electricity consumption (transparency), among others. In the Excel file, there is a tab for each of the suppliers. Biosphere Solar can grade the different criteria based on a Likert grading scale. This grading scale has 5 levels: "Very poor" - 0, "Poor" - 0.3, "Regular" - 0.5, "Good" - 0.8, and "Very good" - 1. It is important that justification of the provided grade is given, to enhance transparency and save considerations that may be useful for future decisions or debate.

Once this is done, the tab "*Supplier selection results*" contains the summary of all the grading in a single table (Table 3). For this table to work, the decision-makers of Biosphere Solar need to weigh the criteria according to their needs. This is done by assigning percentages to each criterion according to their importance, i.e., if one criterion is considered to be more important than the others, the assigned weight is higher. Nevertheless, the sum of the percentages must always add up to 100%.

When the weighting and the grades per supplier is done, the tool calculates the weighted average score and provides a grade for each of them. The higher the value, the better option as a potential supplier. However, it is important to keep in mind that this is just a guideline and that both the grading and the weighting are subjective as they are based on the decision and preferences of Biosphere Solar. Furthermore, an extra recommendation when assigning the grading per criteria is to consider red flags. Red flags are marked with "red" in the criteria description. In case a possible supplier has red flags, it is recommended to give a *very poor* or *poor* grade, regardless of the remaining characteristics.

Table 3: Supplier selection results matrix



	C1	C2	C3	C4	Grade	
Weight	*25%*	*15%*	*10%*	*50%*	*100%*	*The weight is correct*
S1	0.25	0.25	0.50	0.50	**0.40**	**Poor**
S2	1.00	1.00	1.00	1.00	**1.00**	**Very good**
S3	0.00	0.50	0.50	0.25	**0.25**	**Very poor**
S4	0.75	0.25	0.50	0.75	**0.65**	**Regular**
S5	0.00	0.75	1.00	1.00	**0.71**	**Regular**
S6	1.00	1.00	1.00	0.75	**0.88**	**Good**
S7	0.75	1.00	0.75	0.25	**0.54**	**Regular**
S8	1.00	1.00	0.75	0.75	**0.85**	**Good**
S9	0.75	1.00	0.75	0.75	**0.79**	**Regular**
S10	0.75	0.00	0.75	1.00	**0.76**	**Regular**

6 Discussion

The multi-criteria decision matrix developed through this research aims to help Biosphere Solar in selecting sustainable and ethical suppliers. However, it should be noted that the accuracy with which the matrix can be filled out is dependent on the supplier's level of transparency regarding their supply chain. In order to combat the fact that not all suppliers will have answers to all the questions, it was chosen to group the questions into four overarching criteria and assign four overarching scores. While this limits the specificity of the criteria, it ensures that all suppliers can be given a score on all criteria, which is important for being able to make a comparison. Nevertheless, the lack of supplier transparency can make it difficult to evaluate suppliers and hinders a fully comprehensive assessment. It is recommended that the supplier's level of transparency is taken into account when evaluating each criterion, assigning lower scores to those with lower levels of transparency.

Furthermore, it is important to recognize that the ultimate grade given to each supplier is subjective. The criteria scores are based on a qualitative assessment made by Biosphere Solar, and the level of importance that is assigned to each criterion through the weighting scheme is based on Biosphere Solar's values. However, the scores and weights can be easily adjusted in the matrix, making it possible to observe how a different evaluation or prioritization of criteria influences the ultimate supplier ratings.

Lastly, the questions used to guide the scoring of suppliers are based on the raw material and component level findings. The environmental, economic, and social issues identified are limited to the information that is publicly available in the literature and in English. Though two interviews were conducted, confirming several findings, future research would benefit from more interviews with industry experts. This could give further insight into current and best practices as well as more detailed information on specific mining locations or component suppliers.

Despite these limitations, the developed decision matrix can help guide Biosphere Solar navigate the trade-offs involved in selecting sustainable suppliers. Furthermore, it is projected that solar PV will account for nearly 70% of the energy supply in 2050 (Ram et al., 2017), and the European Solar Photovoltaic Industry Alliance was recently introduced to support the expansion of European PV manufacturing and reduce supply dependencies (European Commission, 2023). In light of this growing PV industry and the need to set up sustainable and reliable supply chains, the guidelines provided in this report can be useful for other PV manufacturers as well.

7 Conclusion

This report investigated the main environmental and social concerns associated with the manufacturing of solar panels. The main research question guiding the investigation was "*How can Biosphere Solar navigate through the trade-offs of establishing an ethical and sustainable supply chain for PV module components? ".* To address this question in a manageable way, the problem was divided into three levels of analysis: the raw material level, component level, and supplier level.

Starting with the raw materials required for PV manufacture, the main environmental concerns were: toxins released in the processing of silver ore; open pit mining for copper extraction; and overreliance on foreign countries like China for the sourcing of antimony and silicon. With regards to social sustainability, the biggest red flag was forced labour in the silicon supply chain, and informal and non-regulated mining for tin. These insights can help Biosphere make informed decisions about where it may source its raw materials from.

A similar analysis was conducted for the main components of solar panels such as solar cells, glass, and wiring. Findings show that the production of silicon needed for solar cells is energy-intensive, leading to high impacts on climate change. Additionally, recycling systems for silicon are still underdeveloped, although are estimated to improve over time. Solar glass is currently impossible to recycle due to antimony deposition; this could be solved by using CZTS as an absorption layer instead of antimony. Finally, conductive materials made of silver show strong contributions to human toxicity, freshwater ecotoxicity and abiotic depletion. Copper metallisation could be a promising alternative to silver. For all of the mentioned components, overreliance on foreign countries, especially China, present a supply risk.

As the main research question implies, the perfect sustainable supply chain does not exist. Rather, when selecting suppliers, trade-offs must be made, and improvements on one aspect of sustainability may have unintended negative effects on another aspect. The final multi-criteria decision analysis (MCDA) tool can help Biosphere Solar navigate between such trade-offs, based on the company's own value judgements. The MCDA model currently only reflects the social and environmental dimensions of sustainability, however, it is a flexible tool that could also be adapted to include prices, and other considerations deemed valuable by the user. The hope is that the decision tool, once made available in Biosphere Soar's open-source repository, could help advance supply chain transparency, and improve sustainability practices amongst PV module suppliers.

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