Scenario based life cycle assessment of traditional and non-traditional glass-glass modules with monocrystalline silicon photovoltaic cells – The case of Biosphere Solar technology.

Written by

Fulvia Iannotta

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Student number: 3649156
First supervisor: Carlos Felipe Blanco Rocha, Leiden
University Second supervisor: Malte Ruben Vogt, TU Delft
Case study: Biosphere Solar

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Abstract

This research evaluates the life cycle environmental impacts of traditional and non-traditional glass-glass photovoltaic (PV) modules with monocrystalline silicon cells, with a focus on the novel design by Biosphere Solar. Biosphere Solar module replaces the traditional EVA laminate with PIB edge seal, aiming to enhance material efficiency and reduce environmental impact. A cradle-to-grave scenario-based life cycle assessment (LCA) is conducted to compare the product systems' potential life cycle environmental performance, focusing on different waste treatment strategies. The findings reveal that the traditional PV module design results in higher potential life cycle environmental impacts than the Biosphere Solar module across all selected waste treatment scenarios. Specifically, reusing the silicon wafer in traditional modules leads to lower environmental impacts than solar-grade recycling or incineration. For the Biosphere Solar module, the scenarios involving the reuse of solar cells or silicon wafers show the highest environmental benefits. Therefore, this study concludes that improvements in module designs can significantly reduce environmental impacts by integrating circular economy principles from the product design stage. This integration increases reuse and recycling opportunities, enhancing material efficiency and contributing to a swift and sustainable transition to renewable energy systems.

1. Introduction

The global population is projected to increase by 1.9 billion by 2050, reaching a total of 9.7 billion. As a result, electricity demand is expected to grow by approximately 60% by 2040 (IEA, 2023). Meeting such increase in demand while taking action to prevent a potential climate catastrophe, requires a significant reduction in fossil fuels dependency and a shift to very low- or zero-carbon energy sources. Therefore, the world needs scalable technologies that can generate renewable electricity in stable volumes, and that can ensure material efficiency

(Calvin et al., 2023; IEA, 2023). Not surprisingly, a steady rise of renewable energies deployment for energy generation has been registered throughout the past decades. Among these, photovoltaics (PV) represents one of the most significant renewable energy sources accessible today, providing solid-state, affordable, and effective photon-electron conversion (IEA, 2021).

The International Energy Agency (IEA) has defined solar energy as the cheapest source of new electricity generation in most parts of the world (IEA, 2020). PV energy generation has reached a total cumulative installed capacity of 942 GW in 2021, currently representing the fastest growing source of renewable energy (Blanco, Cucurachi, Peijnenburg, et al., 2020; IEA, 2022). According to recent IEA reports, it is projected to reach a cumulative capacity of 15 TW by 2050, covering approximately 35% of the global electricity mix. The continuous global growth of the PV industry has a strong, positive impact on securing current and future electricity requirements worldwide. However, to fully integrate resource efficiency within such an industry, evaluating the growing volume of future waste streams originating from decommissioned end-of-life PV modules is imperative.

According to projections published by IRENA (2016), the cumulative PV module waste will reach 60 to 78 million tons in 2050 (Sica et al., 2018). Given such forecasts, it is of utmost importance to ensure effective end-of-life management of PV modules - allowing for reuse or recycling opportunities – and hence to address the three main environmental perils that are currently hindering a sustainable transition to a low-carbon energy scenario within the solar industry: (1.1) the emissions generated beyond the operational life of the PV modules, (1.2) PV modules’ linear design discouraging a circular end-of-life pathway, (1.3) and the lack of knowledge regarding effective solar waste handling (Ansanelli et al., 2021; Blanco et al., 2020; Choi & Fthenakis, 2014; Ganesan & Valderrama, 2022; Khalifa et al., 2021; Lim et al., 2022; Peplow, 2022a). These challenges are further discussed in the following sub-chapters.

1.1 Environmental impacts of photovoltaics.

From a life cycle perspective, solar energy is only partially environmentally sustainable. Despite PV modules’ emission-free conversion of sunlight into electricity during their operational life, there are still environmental impacts associated with their remaining life cycle stages: the raw materials extraction, processing, assembly into photovoltaic systems, and end of-life management (Muller et al., 2011). Moreover, these impacts are not merely limited to greenhouse gas emissions but also to the consumption of limited resources, the occupation of land and the emissions of several types of pollutants (Rossi et al., 2023).

The potential life cycle environmental burdens of different types of PV technologies have been largely researched by means of Life Cycle Assessments (LCA) (Blanco, Cucurachi, Dimroth, et al., 2020; Chen et al., 2016; Mariska De Wild-Scholten, 2013; Muller et al., 2011; Sherwani et al., 2010; Wong et al., 2016). LCA is a tool that allows to investigate and quantify all the resources consumed and emissions produced throughout the life cycle of a product system and translate these in terms of impacts to the environment (de Bruijn et al., 2002). As the solar industry is shifting towards monocrystalline silicon modules – currently representing roughly 95% of the total solar PV market share – (ITRPV, 2021; Philipps et al., 2023), it is crucial to investigate which, among the different emerging monocrystalline technologies that are being developed, deliver the highest environmental benefits from a life cycle perspective.

To the best of our knowledge, the study conducted by Müller et al., (2021) is the only LCA focusing on one of the latest developments in module designs of crystalline silicon PV systems. That is, the traditional plastic rear layer (glass-backsheet module or G-BS) is substituted with an additional glass layer (glass-glass module or G-G). This variation is claimed to be favouring

lower degradation rates and hence longer lifetimes compared to conventional G-BS modules. The assessments from Chen et al., De wild-Scholten, and Sherwani et al., (2016; 2013; 2010) also focused on the impact of monocrystalline modules, but they date back respectively to, 2015, 2013, and 2010. Considering the fast pace of module technological enhancement and diversification, the environmental profile of monocrystalline emerging technologies might differ considerably. It is hence necessary to advance research in this field to ensure the transition towards renewable energy sources occurs sustainably.

1.2 Lack of circularity in the solar industry: current end-of-life treatment processes

Current state-of-the-art PV modules are manufactured disregarding the principles of circular economy. This makes them incredibly energy- and cost- intensive if not impossible to recycle, repair or refurbish (Ansanelli et al., 2021; Einhaus et al., 2018). The existing PV module recycling technologies pose challenges not only because of their high energy requirements, but also because they do not facilitate the recovery of module components, once the aluminium frame and the junction box are removed (module disassembly) (Huang et al., 2017). The solar silicon cell, and the electric connectors, usually made of metals such as copper, are encapsulated between ethyl vinyl acetate (EVA). This is the most common material applied as a protective film to shield a PV module's components from outside contaminants, moisture, and mechanical damage (Hasan & Arif, 2014). The front layer is made of glass while the rear layer is commonly made of Tedlar (polyvinyl fluoride, PVF), in combination with PET (polyethylene terephthalate), but can also be replaced with an additional glass layer (Ansanelli et al., 2021; Cattaneo et al., 2015; C. Farrell et al., 2019).

The current mainstream PV module composition makes material separation within the end-of life solar panels highly challenging due to the way the solar cells are laminated and soldered together through the EVA (Sica et al., 2018b). Besides undermining the long-term reliability of PV modules and reducing their lifespan (Cattaneo et al., 2015; Pern et al., 1996), EVA has strong adhesion properties. This means that it glues all the module components to one another permanently making them extremely hard to separate and recover once the panel has concluded its use phase (C. C. Farrell et al., 2020; Sica et al., 2018a). Not surprisingly, the removal of the EVA encapsulation layer – the delamination - has been defined as “one the most challenging steps in the recycling of crystalline silicon PV panels” (Klugmann-Radziemska et al., 2010; Latunussa et al., 2016).

To the best of the author knowledge, three are the main options to perform EVA delamination: mechanical, thermal, and chemical delamination. Among these, mechanical recycling includes relatively simple processes (cutting, peeling, fragmentation, crushing) to separate the various components of the PV sheet and generates relatively low environmental impacts with respect to the other techniques (Ghahremani et al., 2024). This option results in a mixture of materials suitable for low-value applications such as replacing sand, filling concrete slabs, and manufacturing asphalt (Strachala & Hylský, 2017; Tembo & Subramanian, 2023). On the other
hand, thermal and chemical delamination have proven to free the PV sheet from EVA without necessarily generating a mix of crushed materials. By avoiding crushing and shredding activities, it is possible to reclaim entire PV sheet components, allowing for high-value recycling, and possibly also for reuse and repair opportunities (Dias et al., 2021). However, despite allowing for more circular end-of-life strategy, it is important to mention that such treatments also carry the burden of consuming large amounts of organic solvents (chemical delamination), or releasing harmful gasses and requiring high amounts of energy (thermal delamination), (Doi et al., 2001; Xu et al., 2021)

After successfully delaminating the EVA encapsulant, it is possible to recover the glass, the soldering components, and possibly the solar grade silicon if etching and leaching processes are performed (Tembo & Subramanian, 2023). To date, the end-of-life management of a solar module seems to be still quite bleak: most PV modules worldwide find themselves landfilled (C. C. Farrell et al., 2020; Peplow, 2022b) whereas recycling - which only occurs for 10% of modules worldwide - usually only includes glass and metal parts whilst the most precious, and CO2-intensive components to manufacture - the solar cells - are crushed up and used as fillers in products such as asphalt (Zaidi, 2018). It hence appears clear that, to effectively contribute to the decarbonization of the energy system, photovoltaics should be manufactured with a circular end-of-life design, in a way that ideally promotes end-of-life strategies such as recycling or reuse that would ensure material efficiency and recovery.

1.3 End-of-life treatment: there is more than recycling.

Although the materials necessary for PVs production have decreased in quantity over the last few years (Stamford & Azapagic, 2018), there is still significant progress to be made with respect to closing the material loop in the PV module production. This is necessary considering that the predicted growth of the solar PV market will increase the demand for and production of solar panels over the next years (IEA, 2021). Such a surge in PV capacity is associated with an inevitable deluge of solar panel wastes. The cumulative PV module waste will amount to 1.7 to 8.0 million tons in 2030 and to 60 to 78 million tons in 2050 (IRENA et al., 2016; Sica et al., 2018b). In line with the principles of a Circular Economy, PV materials' recovery and reuse both in the PV sector and in different industries would aid in reducing resource depletion while, at the same time, supporting the rising number of solar system installations (Domínguez & Geyer, 2017; Faircloth et al., 2019).

Besides materials such as glass, copper, and aluminium, PV modules also contain very pure silicon, which represents an energy intensive material (Deng et al., 2019) and whose demand - for the PV sector only - is expected to increase from 33 ktons in 2015 to 235 ktons in 2030 in the EU area (Bobba et al., 2018). On the other hand, silicon recovery would avoid the input of energy necessary to extract virgin materials and produce semi-finished products for PV panels. This in turn would reduce the overall life cycle environmental impacts of the PV technologies (Ansanelli et al., 2021; Deng et al., 2019).

As a result, the concerns over photovoltaics' end-of-life waste management have increased over the last years, especially following the 2012 WEEE Directive (2012) which classified photovoltaics as one of the electric and electronic equipment (EEE) and hence established minimum targets for recovery (85%) and recycling (80%) for such wastes. Despite such targets could be achieved by recovering only glass and the aluminium frame (for the case of crystalline silicon PVs), the environmental benefits could be further increased if other valuable minerals like silicon, silver, and copper could be recovered (Ansanelli et al., 2021). This explains the growing interest in investigating different methods for PV panel waste disposal to ensure some level of recyclability and to improve resource efficiency. Several end-of-life strategies of PV technologies were also largely analysed in LCA literature (Ansanelli et al., 2021; Muller et al., 2011), demonstrating that recycling methods are overall ecologically advantageous when compared to other end-of-life scenarios (Latunussa et al., 2016; Stolz & Frischknecht, 2016).

Despite the large body of literature investigating the environmental impacts of PV modules' recycling, there is no study that attempts to investigate alternative end-of-life circular pathways for the different components of PV modules. Put simply, when landfilling and incineration is avoided, recycling seems to be the only solution aiming at recovering some, and not necessarily the most energy intensive, materials. Thus, the need to design PV technologies embedding end of-life circular solutions, namely reuse, repair, or recycling, goes hand in hand with the need to identify the most environmentally sustainable waste treatment *options* and *combinations* to adopt for the different components of emerging monocrystalline silicon PV modules. Consequently, the author of this study seeks to fill this research gap considering the modular PV technology designed by the Dutch start-up Biosphere Solar (BioSolar). The life cycle environmental impacts of such technology are compared to the impacts of a glass-glass PV module with monocrystalline silicon cells (referred in this study as traditional technology). To this end, the next section will describe BioSolar photovoltaics, and according to that, the aim and the novelty of the research are presented together with the research questions, followed by the methodology.

2. Biosphere Solar PV module

An attempt to promote circularity in the solar energy industry is made by the Dutch start-up Biosphere Solar, that designs glass-glass (G-G) modules with monocrystalline silicon cells. As opposed to the traditional technologies, the start-up's modules replace the EVA laminate with an edge seal, a tried and tested technology in the insulating glass (Latunussa et al., 2016; Stolz & Frischknecht, 2016) (Figure 1). By removing the encapsulant Biosphere Solar claims to be increasing the module lifespan up to 50 years due to slower degradation. Furthermore, module disassembly is facilitated, and components are more easily recovered as they are not polluted by EVA residues. In other words, no delamination is required. Therefore, all the different module components are separated once the edge seal is penetrated, and they are ready to be either reused or recycled, depending on their state.

Biosphere Solar module design creates recycling and other circular end-of-life opportunities also for the most energy intensive modules' components (C. C. Farrell et al., 2020; Heath et al., 2020). As the module represents state-of-the-art technology, there is yet no research that attempts to compare its life cycle environmental impacts to the traditional modules available in the market. This might also be explained by the fact that current PV module official datasets and LCA guidelines are still limited to mainstream traditional photovoltaics, making it very difficult to analyse the environmental benefits of new technologies (Frischknecht et al., 2020). Therefore, the aim of this study is to advance research on the life cycle environmental impacts and end-of-life opportunities of newly developed PV technologies.

The gap in research is filled by answering the following research questions: (i) What are the waste treatment combinations among the different module components that ensure the lowest potential environmental life cycle impacts for Biosphere Solar and the traditional technology?

(ii) What are the waste treatment combination among the different module components that generates the highest potential environmental life cycle impacts for Biosphere Solar and the traditional technology?

(iii) Does producing 1kwh of electricity through Biosphere Solar PV technology - which is treated as a waste according to its environmentally best and worst end-of-life combinations - generate lower potential life cycle impacts than producing the same amount of electricity through a traditional technology treated through its environmentally best and worst end-of-life scenarios?

Therefore, aim of this study is twofold. On the one hand, it aims at comparing the life cycle environmental performance of two novel monocrystalline silicon PV modules: a frameless bifacial glass-glass module with monocrystalline silicon cells including the EVA, and the newly developed PV module designed by Biosphere Solar which substitutes the EVA laminate with PIB edge seal. On the other hand, it seeks to shed light on which technology and which end

of-life options – and their combinations – generate the lowest life cycle environmental impacts and that hence should be preferred. As this study focuses on analysing the benefits of circular end-of-life strategies such as high-value recycling or reuse of entire components, only thermal and chemical delamination options are included for the EVA removal of the traditional module. Answering the research questions allows to identify the most environmentally sustainable strategy to apply at the end-of-life stage of the different modules' components. This in turn will contribute to make renewable energy even more sustainable by narrowing, slowing, and closing the material loops in the solar industry. To this end, the following chapter presents the methodology adopted to carry out the study and hence the subsequent chapters.

Figure 4. Left: Conventional module design; Right: Biosphere Solar

Note: From "Biosphere Solar 1" by Biosphere Solar, *Product* (https://www.biosphere.solar/product/).

Figure 1. Left: Conventional module design; Right: Biosphere Solar module design.

module design

3. Methodology

The research questions were answered by conducting first a cradle to grave scenario based LCA comparing 24 end-of-life waste treatment combinations, and consequently an attributional LCA comparing the combinations with lowest and highest potential life cycle environmental impacts. This is done in accordance with ISO 14040 and 14044 guidelines. Thus, the study is divided into four phases: the goal and scope definition, the life cycle inventory analysis, the life cycle impact assessment, and the interpretation (Curran, 2013). The goal and scope definition outlines the research objective, sources, and assumptions of the study. It establishes the system boundaries, the functional unit, and its corresponding reference flow. Following this, the life cycle inventory (LCI) gathers data on all inputs and outputs for each

unit process within the specified product systems. Subsequently, the life cycle impact assessment (LCIA) calculates the potential environmental impact of the product systems. The LCI results are quantified for the selected impact categories, utilizing characterization factors that convert the assigned LCI results to the common unit of the category indicator. Finally, the results are analysed and presented during the interpretation phase. This phase involves pinpointing environmental hotspots, formulating limitations, and drawing conclusions that align with the study goal and scope.

To answer the first and second research question, and hence, to pinpoint the best and worst environmentally sustainable end-of-life solutions, different waste treatment activities, namely reuse, recycling, incineration, thermal and chemical delamination were evaluated. The modelling choice of "avoided product" was selected for the option of reuse and recycling of components, to account for the environmental benefits of avoiding the production of the corresponding virgin material. The selected waste treatment options were combined for the different PV module's components (the EVA encapsulant for the traditional module, the glass sheet, copper and tin for the soldering and the junction box, and the silicon solar cells) by means

of parameters to eventually assess 24 end-of-life scenarios that can be found in tables 1 and 2. For instance, to evaluate the end-of-life scenario combining the reuse of the glass sheet, of the copper and tin used for soldering, and of the solar cell for the Biosphere Solar module (option 1), the parameters s6=1, s7=1, and s8=1 were assigned to the material flows corresponding to those end-of-life options. Alternatively, such parameters were set as equal to 0, when assessing the combination of glass, copper, tin, and solar grade recycling (option 12). The possible end of-life treatment options are listed for both technologies in the Appendix 1 and 2, whereas a more comprehensive version of tables 1 and 2, including the assumptions made to estimate the different flows of materials, wastes, and electricity, is available in the supplementary material.

The scenario based LCA allows to generate a wide range of possible impact results expressing the eco-profile of emerging PV technologies designed in line with the principles of circular economy versus the impacts of traditional technologies. Consequently, the options reflecting the lowest and highest life cycle environmental impacts for the selected impact categories are compared and set as default for answering the last research question. The next chapters present accordingly the different phases of the LCA. Therefore, the waste treatment processes for the different components were modelled considering the type and quantities of materials flowing into the process of PV module production. Such materials were allocated to the different module's components, scaled consistently with the reference flow of the study, and converted into wastes to be treated by means of Ecoinvent v3.9 proxies. For instance, waste aluminium, waste glass, and waste electric and electronic equipment were selected as the wastes reflecting the waste treatment of BioSolar glass sheets (that reflect the double-glass technology and hence include materials such as aluminium and polybutadiene).

Table 1: end-of-life options combined into 12 scenarios for Biosphere Solar PV module.

End-of-life treatment Scenario combinations for Biosphere Solar module											
Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario 11**	**Scenario 12**
Glass reuse (s6=1)	Glass reuse (s6=1)	Glass reuse (s6=1)	Glass reuse (s6=1)	Glass reuse (s6=1)	Glass reuse (s6=1)	Glass recycling (s6=0)	Glass recycling (s6=0)	Glass recycling (s6=0)	Glass recycling (s6=0)	Glass recycling (s6=0)	Glass recycling (s6=0)
Copper and tin reuse (s7=1)	Copper and tin reuse (s7=1)	Copper and tin reuse (s7=1)	Copper and tin recycling (s7=0)	Copper and tin recycling (s7=0)	Copper and tin recycling (s7=0)	Copper and tin reuse (s7=1)	Copper and tin reuse (s7=1)	Copper and tin reuse (s7=1)	Copper and tin recycling (s7=0)	Copper and tin recycling (s7=0)	Copper and tin recycling (s7=0)
Solar cell reuse (s8=1; s9=0; s10=0)	Wafer reuse (s8=0;s9=1;s10=0)	Solar grade recovery (s8=0; s9=0; s10=1)	Solar cell reuse (s8=1; s9=0; s10=0)	Wafer reuse (s8=0;s9=1;s10=0)	Solar grade recovery (s8=0; s9=0; s10=1)	Solar cell reuse (s8=1; s9=0; s10=0)	Wafer reuse (s8=0;s9=1;s10=0)	Solar grade recovery (s8=0; s9=0; s10=1)	Solar cell reuse (s8=1; s9=0; s10=0)	Wafer reuse (s8=0;s9=1;s10=0)	Solar grade recovery (s8=0; s9=0; s10=1)

Table 2: end-of-life options combined into 12 scenarios for traditional PV module.

End-of-life treatment Scenario combinations for the traditional module											
Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario 11**	**Scenario 12**
Thermal delamination (s1=1)	Thermal delamination (s1=1)	Thermal delamination (s1=1)	Thermal delamination (s1=1)	Thermal delamination (s1=1)	Thermal delamination (s1=1)	Chemical delamination (s1=0)	Chemical delamination (s1=0)	Chemical delamination (s1=0)	Chemical delamination (s1=0)	Chemical delamination (s1=0)	Chemical delamination (s1=0)
Glass recycling (s2=1)	Glass recycling (s2=1)	Glass recycling (s2=1)	Glass incineration (s2=0)	Glass incineration (s2=0)	Glass incineration (s2=0)	Glass recycling (s2=1)	Glass recycling (s2=1)	Glass recycling (s2=1)	Glass incineration (s2=0)	Glass incineration (s2=0)	Glass incineration (s2=0)
Wafer recovery (s3=1; s4=0; s5=0)	Solar grade recovery (s3=0; s4=1; s5=0)	Solar cells incineration (s3=0; s4=-; s5=1)	Wafer recovery (s3=1; s4=0; s5=0)	Solar grade recovery (s3=0; s4=1; s5=0)	Solar cells incineration (s3=0; s4=-; s5=1)	Wafer recovery (s3=1; s4=0; s5=0)	Solar grade recovery (s3=0; s4=1; s5=0)	Solar cells incineration (s3=0; s4=-; s5=1)	Wafer recovery (s3=1; s4=0; s5=0)	Solar grade recovery (s3=0; s4=1; s5=0)	Solar cells incineration (s3=0; s4=-; s5=1)

4. Goal and scope definition

4.1 Goal

The main goal of this study is to evaluate the influence of module design on the life cycle potential environmental impacts of emerging glass-glass PV modules with monocrystalline silicon cells. Biosphere Solar's module replaces the EVA laminate with PIB edge seal compared to the traditional technology (see Figure 1). The production location studied is China, which currently represents the largest producers of modules' components (Philipps et al., 2023). However, the PV modules are assumed to operate in The Netherlands and treated as a waste in Germany. End-of-life activities are assumed to take place in one single location in Germany.

Furthermore, the product systems' environmental hotspots will be identified, especially focusing on different end-of-life treatment combinations for the different modules' components. This information will support informed decisions regarding Biosphere Solar's product development and improvements before its commercialization. Information about the two module parameters is listed in Table 3.

The assessment is conducted by Fulvia Iannotta, student of the master's degree in industrial ecology taught at the University of Leiden, the Netherlands, as part of her master's thesis project. The commissioner is the Delft-based start-up Biosphere Solar. The supervising committee and expert reviewers are professors Carlos Felipe Blanco Rocha and Malte Ruben Vogt, from Leiden university and TU Delft university respectively. Together with the commissioner of this assessment, they represent the target audience of this research project. The ISO 14040-44, the Methodology Guidelines on Life Cycle Assessment of Photovoltaic from IEA, and the "Product Environmental Footprint Category Rules (PEFCR) for PV modules are followed along the different phases of the study to assure consistency, transparency, and quality (de Bruijn et al., 2002; Frischknecht et al., 2020). Divergences from the suggested methodological guidelines are explicitly mentioned. This assessment does not aim at public comparative assertion.

A scenario based LCA is chosen as methodology for this study because it allows for the quantification of all the resources consumed and emissions produced throughout the life cycle of the alternatives considered according to the specific end-of-life treatment option selected. This, in turn, allows the comparison of Biosphere module design with respect to the standard technology and hence the understanding of the effective environmental gains achieved when changing the module design. Additionally, the analysis of different end-of-life solutions allows for the identification of the most environmentally sustainable strategies to apply at the end-of life stage of the different modules' components. Simply put, this study will clarify if and to which extent, from a life cycle perspective, BS module is more environmentally sustainable than its traditional technology. Furthermore, the identification of the environmental hotspots associated with the end-of-life of the PV module will provide valuable information on how to treat the different waste components to minimize the environmental impacts of the modules.

Table 3: PV module parameters for the alternatives considered

4.2 Scope

The potential life cycle environmental impacts of Biosphere Solar modules and the traditional technology are investigated through an attributional LCA. Temporal scope wise, this research aimed at gathering the most recent data *available*. The geographical scope varies according to the life cycle phase: China reflects the location where extraction of raw materials, their processing and assembly occur. The installation and operation occur in The Netherlands, and end-of-life treatment are performed in Germany. Hence, the technology coverage is adapted to reflect the technology mix of the country from which the different life stages occur. This study follows a cradle-to-grave perspective, and its system boundaries are illustrated in Figure 2. The entire production chain of single-crystalline silicon PV panels, transport to installation location and different waste treatments are included. As the alternatives are assumed to have similar weight and area, and hence to require same quantities of materials for BOS, this is excluded for difference analysis.

The LCA software used to conduct this study is OpenLCA, while the LCI databases used are Ecoinvent v3.9 and the IEA datasets. The IEA PV LCA guidelines (Frischknecht, 2020) recommend addressing the midpoint indicators of the PEFCR for the life cycle impact assessment stage. Thus, the environmental impacts are measured in terms of the different impact categories indicated by such guidelines. The functional unit is quantified in terms of kWh, following the IEA guidelines. This allows to investigate the potential environmental gains obtained with increased module lifetime. The refence flow reflects the module surface area needed to produce the functional unit of 1kwh, which corresponds to 6.56275E-05 m2/kwh for both technologies when their lifetime is set as 30 years. Additional information relative to the reference flow calculations can be found in the supporting material.

5. Life cycle inventory analysis

The following sub-chapters provide an overview of the data gathering, limitations, and main assumptions made to conduct the life cycle inventory analysis of this study. The full list of assumptions e modelling choices is available in the supplementary material providing unit process data.

5.1 System boundaries, cut-offs, flowchart

This study covers the entire supply chain of the product systems under analysis (cradle-to grave). Therefore, it encompasses the following economic flows: metallurgical-grade silicon production, solar grade silicon production, silicon production through the single crystal Czochralski process, and module transportation, as back-ground processes. The production of photovoltaic PERC cells, the panels production, the electricity generation, as well as the different end-of-life processes are included and modelled as foreground processes. The installation and balance-of-system are excluded for difference analysis. To the best of the author knowledge, no cut-offs are made in this study. Reuse, recycling, and incineration are considered as possible end-of-life treatment processes for the different components of the modules. The end-of-life phase is divided and modelled according to the different PV module's components, namely the disassembly (removal of the junction box), the encapsulant delamination, glass sheet recovery, soldering removal, and solar cells recovery. All the processes are displayed in figure 2

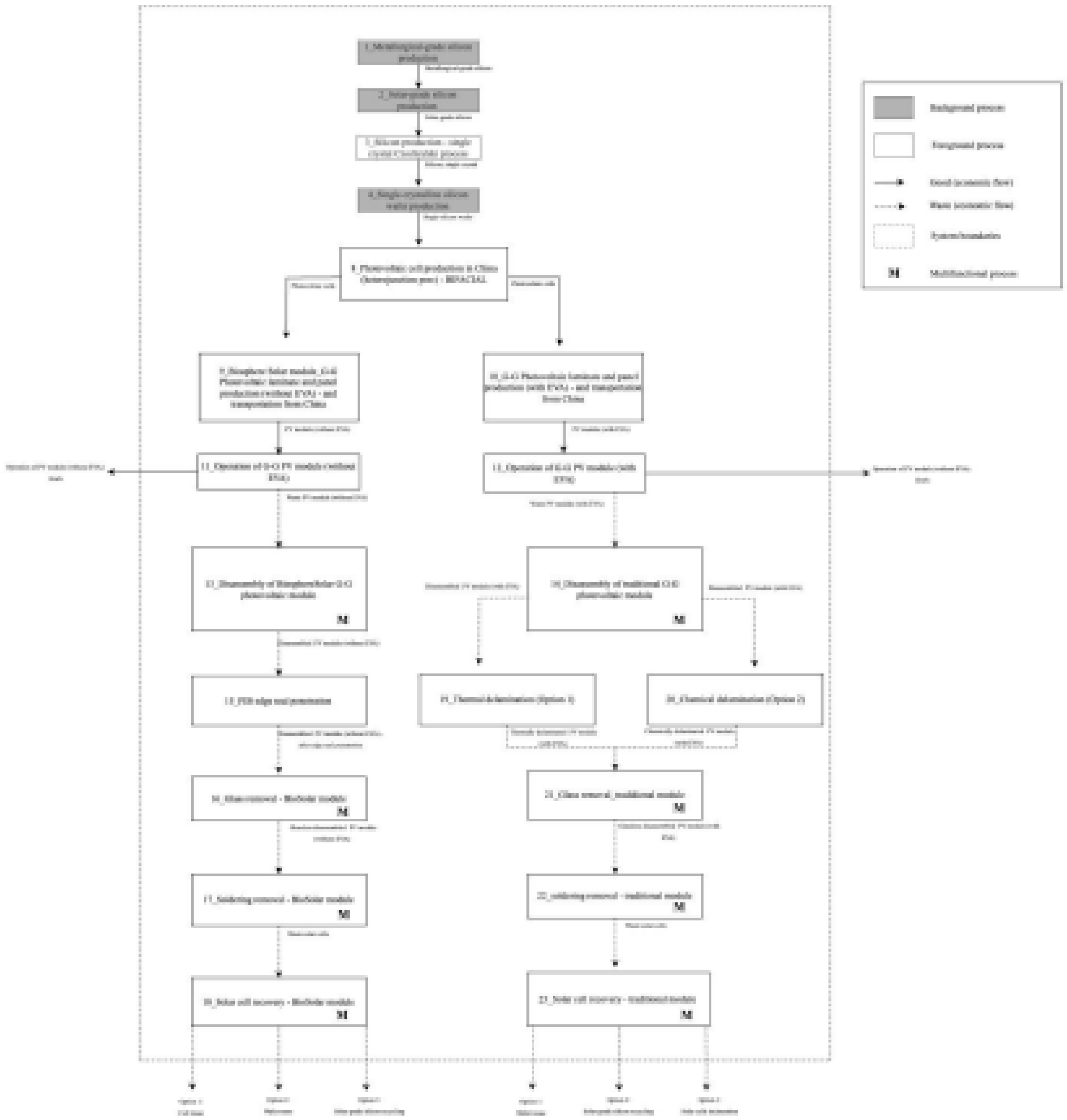

Figure 2. System boundaries.

5.2 Data collection, modelling choices, and limitations.

Comprehensive data collection was undertaken for all processes within the respective product systems, and thorough documentation of assumptions and calculations is available in the supplementary materials. The IEA PVPS Task 12 (Frischknecht, 2020) in 2020 and the Ecoinvent v3.9 database are the primary source of background life cycle inventories. Although these sources provide the most recent, comprehensive LCI compilation available on photovoltaic (PV) systems they do not sufficiently represent state-of-the-art innovations of the current PV production and end-of-life treatments. Thus, they were supplemented with data from literature, proxies, or assumptions (Einhaus et al., 2018; Huang et al., 2017; Louwen et al., 2015; Lunardi et al., 2018; Müller et al., 2021; Wang et al., 2019) to reflect PV module technological developments - like the production of glass-glass modules (as opposed to inventories only proving data for glass-backsheet modules), or the technological changes implemented by the start-up the Biosphere Solar (i.e., insulating glass technology and EVA removal) - and to model the end-of-life scenarios.

Among the various modelling choices, it is relevant to mention that for the Ecoinvent v3.9 process "silicon production, single crystal, Czochralski process, photovoltaics", the amount corresponding to the inflow of electronic grade silicon is assumed to be solar grade silicon. This was done to reflect significant increases in solar grade silicon production, and the subsequent reduction of scrap silicon from other industries, as a consequence of the tremendous growth in silicon demand in the PV industry (Frischknecht et al., 2020; Yue et al., 2014).

Similarly, to reflect the production of bifacial heterojunction photovoltaic cells, the following modelling decisions were made starting from the process of PERC cell production retrieved from Müller et al., (2021): on the one hand, the process parameters for plasma-enhanced chemical vapour deposition (PECVD) of amorphous silicon thin films provided by Louwen et al., (2015) were collected and readapted to be consistent with the product system under analysis. On the other hand, the amount of metal inflow was reduced by 70% to reflect the fact that for bifacial cells the rear side of the module has lower amount of metal with respect to the monofacial modules.

For what concerns the end-of-life treatment processes, the waste treatment options included in this assessment lack of comprehensive publicly available data for detailed analysis. Consequently, reproducing these processes through assumptions and estimations was necessary to accurately simulate their environmental impacts. The waste treatment processes for the different components were modelled considering the type and quantities of materials flowing into the process of PV module production. Such materials were allocated to their corresponding module's components, scaled consistently with the reference flow of the study, and converted into wastes to be treated by means of Ecoinvent v3.9 proxies. For instance, waste aluminium, waste glass, and waste electric and electronic equipment were selected as the wastes reflecting the waste treatment process for the BioSolar glass sheets (that reflect the insulating glass technology and hence include materials such as aluminium and polybutadiene). Additionally, to account for some material losses in the various components' recycling processes, only 90% of the initial material was assumed to be recovered through the avoided burden modelling choice, whereas the remaining 10% was assumed to be flowing out of the system boundaries

as a waste. 100% of material recovery was rather assumed for reusing scenarios, which was also accounted through the avoided burdens modelling choice.

With respect to the energy inputs adopted in the study, it is crucial to make two considerations

First, all the electricity inflows for the different end-of-life scenarios considered reflect current energy grids, although attempting to reflect processes such as reuse or high-value recycling which are currently not occurring in real life. Therefore, when such circular end-of-life treatment options will be applied in the future, it is likely that they will rely on different energy grids, and result in different magnitudes of impacts. Secondly, the electricity inflows amounts were assumed proportionally to the corresponding energy flowing into the production processes of the different PV modules' components. This was done to compensate the lack of detailed inventory data relative to the different end-of-life PV module processes and components. For instance, 10% and 50% of the quantity of electricity required to produce the glass component, scaled to the reference flow of the study, were selected to reflect the energy requirements for the options of glass reuse and recycling, respectively.

A different approach was taken for the energy requirements of the silicon solar cells recovery scenario, to reflect that the silicon components are the most valuable to recover. In this case, 1% of the electricity needed to produce the photovoltaic cells was used for the solar cells reuse scenario. For the scenario of wafer reuse, it was assumed that such option implied the subsequent process of solar cells production. Thus, the quantity of electricity necessary to produce the solar cells - scaled to the reference flow of the study - was assumed to be representative of the wafer recovery process. Similarly, the scenario of solar grade recycling, would require the subsequent processes of silicon production - single crystal Czochralski -, the wafer production, and solar cell production, to regain the solar cells. Thus, the quantity of electricity for such processes was summed and scaled to reflect the electricity needs for the scenario of solar grade recycling. Lastly, the solar cells incineration assumed that virgin material would be required to obtain the final product again, and hence considered all corresponding supply chain electricity requirements, scaled to the reference flow of the study.

A final consideration goes to the modelling of the EVA delamination processes for the traditional PV modules. Environmental flows generated by the process of pyrolysis (thermal delamination) were retrieved from Wang et Al., (2019). However, it was only possible to retrieve the type and not the quantity of gasses generated by such process. Thus, their corresponding amounts, and the energy needs were calculated through simplified assumptions (available for consultation in the supplementary material). Similarly, the quantity of solvent flowing into the process of chemical delamination was also determined through assumptions, and hence might reflect the result of an overestimation. These assumptions were made to overcome the obstacle of data unavailability. They reflect the researcher's attempt to recreate the most realistic and consistent processes estimations. Nonetheless, as they do not reflect official data, it is fundamental to interpret the research results with respect to the specific systems studied and their respective assumptions and limitations.

6. Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in which the inventory analysis results are further processed and interpreted in terms of environmental issues of concern (Guinée et al., 2002). The midpoint indicators of the PEFCR guidelines (TS PEF Pilot PV 2018; European Commission 2017; Fazio et al. 2018) were considered for this study, as indicated by the IEA LCA methodology guidelines (Frischknecht, 2020). However, this study diverges from such guidelines by excluding the additional complementary indicators, namely those quantifying the radiotoxicity potential of nuclear waste, the renewable cumulative energy demand, and the biodiversity damage potential caused by land use. This decision does not reflect a dismissal of the importance of these indicators, but rather the researcher decision to focus on the core metrics relevant to the scope of this assessment.

Characterization models are used to determine how certain environmental interventions contribute to a specific environmental impact. The indicator results were calculated by multiplying the inventory results by their corresponding characterization factors. By using a reference substance for a given impact category, the unit of the category indicator was expressed in equivalent of the reference substance, and they differ according to the impact category. In this phase of the LCA, a scenario-based LCA is firstly performed to answer the first and second research question. Once the waste treatment options generating lowest and highest environmental impacts are individuated, a more comprehensive LCA is performed to compare the potential life cycle environmental impacts of both technologies when their environmentally worst and best options are considered. In other words, the third research question is answered.

6.1 Scenario-based LCA: LCIA results

Twelve different end-of-life combinations were analysed for both alternatives with respect to PEF LCIA method (v3.1). The impact categories climate change, particulate matter, and resource utilization (metals and minerals resources) were selected to pinpoint the scenarios reflecting lowest and highest environmental impacts for both technologies. The choice of focusing on these impact categories is justified by the fact that they are considered as the most relevant for single-crystalline silicon PV systems (PEFCR, 2019). To gain a broader perspective on findings for all impact categories, readers are encouraged to refer to Appendix 3 and 4. Overall, results show that scenarios including the option of PV cell incineration (option 3,6,9, and 12) for the traditional PV module reflect the highest potential life cycle environmental impacts across all impact categories. On the contrary, all the end-of-life combinations that include the option of wafer reuse (option 1,4,7,10) represents the combinations generating not only lowest but also in some cases positive environmental impact. For what concern the case of Biosphere Solar PV module, findingsreflect lowest environmental impacts for scenarios including the option of solar cell reuse and highest impacts for the combinations including solar grade recycling. Results are further discussed in sections 6.2, and 6.3, and options 1 and 12 are further analysed for both alternatives in section 7.

6.2 Traditional module LCIA results

In the assessment of the environmental impacts associated with the traditional PV module, results indicate that treating the module as waste according to Option 1 yields the most environmentally preferable outcomes. This option involves thermal delamination (pyrolysis of EVA), glass recycling, and silicon wafer reuse. Conversely, Option 12, which includes chemical delamination, glass incineration, and solar cell incineration, generates the highest environmental impacts. Specifically, for the impact category of climate change, Option 1 has a negative value of -3.98E-03 kg of CO2-Eq, indicative of its positive environmental contribution. This is followed respectively by options 4, 7, and 10, all including the reuse of the wafer.

Results show that the impact on climate change increases as waste treatment strategies different from reuse are selected. For example, producing 1kwh of electricity with a traditional PV module treated as waste according to option 7 and 10 (chemical delamination, glass recycling, wafer recycling) generates 1.36E-03 kg of CO2-Eq. In contrast, Option 12 exhibits the highest impacts, with a value of 1.66E-02 kg of CO2-Eq. This is followed by option 9, 11, 8, 6, and 3
in terms of highest environmental impacts, generating respectively 1.59E-02, 1.35E-02, 1.27E 02, 1.12W-02 and, 1.05E-02 kg of CO2-Eq.

For the impact category of resource use, Option 1 generates 9.49E-08 kg of Sb-Eq, reflecting the lowest depletion of metals and minerals resources. In contrast, Option 12 yields an impact of 1.30E-07 kg of Sb-Eq, indicating higher resource depletion. For what concerns the impact assessment of particulate matter, Option 1 still generates the lowest potential life cycle environmental impacts, with a negative value of -6.65E-11 disease incidence, suggesting a reduction in health impacts associated with particulate matter formation. Conversely, Option 12 exhibits a value of 7.63E-10 disease incidence, indicating a less favourable impact on human health.

All in all, option 1 emerges as the environmentally preferable waste treatment option, whereas option 12 represents the least favourable strategy, generating highest environmental impacts across multiple impact categories. Therefore, option 1 and 12 are selected for further analysis and comparison with respect to the impacts generated by the Biosphere Solar technology. The results for the above-mentioned impact categories are depicted according to the different waste treatment options in figures 3, for climate change, and in Appendix 5, and 6 for the case of material resource utilization, and particulate matter formation.

Figure 3. LCIA results for climate change, traditional PV module.

6.3. Biosphere Solar LCIA results

The waste treatment options for the Biosphere Solar PV module yield significant differences in life cycle environmental impacts. Notably, producing 1 kWh of electricity through the Biosphere Solar PV model results in the lowest environmental impacts when treated as waste according to Option 1. This option incorporates the reuse of glass sheets, copper, and tin for soldering components, along with solar cell reuse. On the other hand, the highest environmental impacts occur when the module is treated as waste according to Option 12, which includes glass, copper, tin, and solar grade recycling.

For the impact category of climate change, Option 1 demonstrates a notably positive environmental impact, with a value of -8.67E-03 kg of CO2-Eq, while Option 12 generates 9.18E-03 kg of CO2-Eq. Similarly, across other impact categories, Option 1 consistently yields negative values, indicating overall positive environmental impacts. For instance, for the case of resource use, Option 1 results in -4.10E-07 kg of Sb-Eq, whereas Option 12 yields 1.27E

07 kg of Sb-Eq. Additionally, for the impact on particulate matter, Option 1 has a value of -

2.74E-10 disease incidence, while Option 12 results in 5.71E-10 disease incidence.

All the waste treatment combinations including the option of PV solar cell reuse, follow option 1 in terms of lowest environmental impacts. On the contrary, option 6 and 9 – both including solar grade recycling – follow option 12 in terms of highest environmental impacts across the different impact categories considered. Therefore, option 1 and 12 are selected as the environmentally best and worst options, and they are further analysed and compared against the impacts of the traditional PV technology (options 1 and 12). A visual representation of the different environmental impacts across the different 12 options is available in figure 4, for the case of climate change, and in Appendixes 7, and 8, for impacts on material resource utilization, and particulate matter formation.

Figure 4. LCIA results for climate change, Biosphere Solar PV module.

7. Life cycle impact assessment for waste treatment options 1 and 12 The inventory tables were calculated considering options 1 and 12 for both Biosphere Solar PV module, and for the traditional PV module. They are available in the supplementary material. The list of all the generated environmental outflows represented the input to obtain the characterization results, presented in the next section.

7.1 Characterization results

Characterization results compare Biosphere Solar and the traditional technology options reflecting lowest potential life cycle environmental impacts – options 1 – and those generating the highest life cycle environmental impacts, that are, options 12 for both alternatives. Given the diverse units and scales of impact categories, the characterization results are represented on a unit scale for both options 1 and 12. This scale sets the impact of the traditional module at -1 or +1 (depending on the negative or positive value of the corresponding category indicator result) for comparative analysis. These findings facilitate the determination of which alternative exhibits superior performance concerning specific impact categories, as depicted in figures 5, and 6.

Starting from the waste treatment options generating the lowest potential environmental life cycle impacts, the characterization results reveal that the environmental performance of the traditional PV module and the Biosphere Solar technology varies across different impact categories. However, Biosphere Solar PV module outperforms the traditional technology across all impact categories. For instance, producing 1kwh of electricity through a traditional PV module that is treated as a waste through thermal delamination, glass recycling, and wafer reuse, would generate 4.39E-03 kg of CO2-Eq. In contrast, producing the same amount of electricity with the Biosphere Solar module treated as waste according to option 1 (glass, copper, tin, and solar cells reuse) would avoid the emissions of 8.67E-03 kg of CO2-Eq. Thus, the positive impact of the latter corresponds to roughly two times the impact of the former. Therefore, when considering these end-of-life combinations, the newly developed technology has a lower carbon footprint and contributes less to climate change compared to the traditional technology.

Similarly, for the impacts on ozone depletion, freshwater ecotoxicity, human toxicity (carcinogenic, inorganics), freshwater ecotoxicity (inorganics), producing 1 kWh of electricity with the traditional PV technology exhibits significantly higher environmental impacts compared to the Biosphere Solar technology, equivalent to 14.10, 7.36, 7.95, and 8.72 times lower than the impact generated by the PV module without EVA. Overall, producing 1kwh of electricity through Biosphere Solar technology treated according to option 1 one would generate positive environmental impacts across all impact categories. In contrast, the mainstream technology does contribute to negative environmental impacts on human toxicity (non-carcinogenic, organics and carcinogenic, organics), material resources (metals and minerals), and land use.

On a similar pattern, the newly developed glass-glass technology from BioSolar performs environmentally better than the traditional one, even when waste treatment combinations 12 are compared. Despite not generating any positive environmental contributions, the impact of producing 1 kwh of electricity through the Biosphere Solar technology that recycle glass, copper tin, and solar grade silicon, is still lower than producing the same amount of electricity with a traditional PV module in which the EVA is chemically delaminated, copper and tin recycled, and glass and solar cells are incinerated. As depicted in figure 6, the sharper differences in impact can be found with respect to the impact on climate change, energy resource (non-renewable), human toxicity (non-carcinogenic, organics), and water use, for which the impact of the Biosphere Solar technology only represents 18%, 27%, 29%, and 30% the impact of the traditional module, respectively. On the other hand, the difference in material resources impact between the two alternatives is less pronounced. Biosphere Solar impact on material resources indeed constitute 90% the impact of the traditional module, reflecting a difference in impact of only 10 percentage points.

Figure 5. Characterization results for the two alternatives (options 1)

Figure 6. Characterization results for the two alternatives (options 12)

8. Interpretation

The interpretation phase of an LCA evaluates the results from the life cycle impact assessment to derive conclusions and recommendations. It aims to identify significant environmental issues, assess data quality, and ensure consistency with the study's goal and scope. To this end, a consistency and completeness check is performed in section 8.1 and 8.2. This is followed by a contribution analysis to pinpoint the environmental hotspots for both product systems, and a sensitivity analysis in performed to assess the robustness a reliability of the results (8.3 and 8.4). Finally, limitations are listed, results are critically discussed and compared to other studies, and conclusions are drawn in sections 9, 10, and 11.

8.1 Consistency check

A consistency check was performed to ensure consistency between data, assumptions, models, and methods used and hence the study alignment with its goal and scope. Only the items for which differences were found, and hence differences in data sources and data accuracy between the two alternatives, are discussed in this section. For what concerns the former, the main source of data was used for most of the unit process, namely the IEA life cycle inventories for photovoltaics, and the Ecoinvent databases v3.9. However, as this study performs a detailed analysis of end-of-life treatment processes that are not extensively covered in the above mentioned documentations, alternative data source and estimations had to be made for the different product systems.

For example, environmental flows generated by the pyrolysis of EVA, which is not required for the case of Biosphere Solar module, were gathered from literature (Wang et al., 2019). On the other hand, information on PIB edge seal penetration for BioSolar module were gathered from Einhaus et al., (2018), and they did not provide any information on environmental flows included in such process. Additionally, the Biosphere Solar technology represent a state-of-the art improvement of traditional modules available in the market. Consequently, data reflecting its production is yet not available. Thus, the differences in module designs were accounted starting from data relative to the traditional technologies. For example, the inflows of the EVA were removed from the process of Biosphere Solar module production.

Therefore, differences in data accuracy might exist between the different life cycle stages, rather than between the two technologies considered. In other words, official and thorough data is not available for the end-of-life processes of photovoltaics. As an attempt to investigate on and account for the potential environmental impacts of the different end-of-life options, data available from literature was used and assumptions were made to produce the most realistic estimations of such processes. Thus, a less complete coverage of economic and environmental flows occurs for the end-of-life processes of both technologies. However, as assumptions made correspond to the only available knowledge and data available, they are assumed to be representative of real activities and hence in line with the goal and the scope of this LCA.

8.2 Completeness check

Completeness of data and information was examinate by the researcher of the study. Both PV modules considered were analysed from a cradle-to-grave perspective, excluding the balance of-system and installation, for both product systems. Such methodological choice, made also in similar LCA studies (Müller et al., 2021), was made because the same PV module parameters were considered for both alternatives. Beside the removal of EVA, the only difference in PV module design is given by the double-glass technology in the Biosphere Solar module, which is not assumed to imply difference in the balance-of-system requirements.

Additionally, the detailed focus on the different end-of-life treatment process for both technologies implied estimations and assumptions to account for the unit processes' inflows and outflows. This choice was essential due to the unavailability of complete and detailed data for waste treatment process from the IEA life cycle inventory for photovoltaics (Frischknecht et al., 2020). As different waste treatments are required for the different technologies, divergencies in completeness might have occurred despite trying to reflect the most accurate flow exchanges. This is the case, for example, for the processes of EVA delamination for the traditional module and PIB edge seal penetration process for the Biosphere Solar module. Due to the lack of data availability, assumptions made are considered as the best available estimations of the studied processes. Thus, both product systems provide a satisfactory representation given the data available for this study, and the flowcharts are complete and in line with the scope of the study.

8.3 Contribution analysis

Contribution analysis was performed to understand the impact of different processes on climate change, resource use, and particulate matter formation. This was done for both PV modules and for the waste treatment combinations 1 and 12 (calculations are available in the supplementary material). The selection of the avoided burden approach to account for the environmental benefits of recycling and reuse for the various modules' components led to negative contributions for certain waste treatment processes, indicating a net environmental benefit rather than a burden. Despite some processes having negative contributions, the sum of all contributions is still equal to 100%. This is because the negative contributions were subtracted from the total, balancing out the positive contributions. The overall sum represents the net environmental impact after accounting for both burdens and avoided burdens. The different contribution analyses are discussed below, and their corresponding graphical representations are available in Appendixes 9, 10, 11, and 12.

8.3.1 Contribution analysis for the traditional PV module (waste treatment strategy 12)

The highest impact on climate change is generated by the processes of chemical delamination, and solar cell incineration which contribute to 34.25% and 19.50% of the overall impact to climate change. Nearly all the impact generated by the former is due to the production of toluene, which is the solvent needed to perform the activity. The high contribution of the latter is caused by the electricity input necessary to perform the activity. The electricity requirement is indeed responsible for generating nearly 100% of the overall emissions generated by this process. A positive contribution to climate change impact is generated by the process of PV module disassembly and soldering recycling, as they allow for copper and tin recycling. They contribute to avoiding CO_2 equivalent emissions equal to 6.00E-05 and 5,40E-05 kg.

For what concerns the contribution to material resources utilization, the highest impacts are generated by the process of PV module production and PV cell production, contributing 76.72% and 113.81% respectively. Of the total contribution generated by the former, 53.63% and 14.12% derive from the inputs of copper and tin. On the other hand, 85% of the PV cell production contribution is due to the process of metallization paste production. However, such high percentages are offset by the environmental benefits of the soldering materials recycling and the PV module disassembly. The former reduces the overall impact on resource use by 56.03% through the recovery of tin and copper, and the latter by 48.22% through the recovery of copper from the junction box.

8.3.2 Contribution analysis for Biosphere Solar PV module (waste treatment strategy 12)

Silicon production (single crystal Czochralski process), PV module production, and solar grade silicon production correspond to the activities that mostly contribute to the impact of Biosphere Solar technology treated according to waste treatment option 12. They contribute to 24.36%, 20,31%, and 22.76% the overall impact on climate change. On the other hand, all the waste treatment options that include the recycling of the module components positively contribute to the overall impact to climate change. In other words, they contribute to reduce the overall impact to such impact categories. The highest benefits are achieved through the recycling of the glass (-15.51%), and the recycling of tin and copper from the soldering component and the junction box. Interestingly, the environmental gains of recovering the solar grade silicon do not outweigh the emissions generated for the electricity requirements of its recycling process. Therefore, the process of solar grade recycling does not positively contribute to the climate change impact. However, the emissions generated by the recycling of solar grade are roughly the half of those generated when virgin material is produced (1.03E-03 vs 2.46E-03 kg of CO2- Eq).

The solar cells and PV module production processes highly contribute to depletion of materials, mainly through metallization paste production - with silver highly affecting this impact – but also copper and tin. However, the recycling of copper, glass, tin, and solar grade positively contribute, and hence reduces, the overall impact on resource utilization. Additionally, PV module production, silicon production (single crystal Czochralski process), and solar grade silicon production are responsible for 36.66%, 33,38%, and 30.99% of the overall contribution to particulate matter formation. Similarly to the impact on climate change and material resources utilization, also in this case, glass recycling, PV module disassembly, soldering recycling, and particularly solar grade recycling (-11.17%) contribute to reducing the impact on particulate matter formation.

8.3.3 Contribution analysis for the traditional PV module (waste treatment strategy 1)

The processes of glass and soldering recycling, and silicon wafer reuse contribute to -23.28%, -0.96%, and -256% to the overall climate change impact, and -101.14%, -9.74%, and -483.23% to the impact on particulate matter formation. The negative values indicate that these stages are reducing the overall environmental impact of the system. On the contrary, the processes of silicon production, solar grade silicon production, and PV module production are the largest contributors to the above-mentioned impact categories representing 44.28%, 41.38%, and 36.68% the of the climate change total impact, and 133.06%, 123.57%, and 123.85% for the case of particulate matter formation

A similar pattern is observed for the impact on resource use. It emerges that recycling the module components and especially reusing the silicon wafer reduces the overall impact on material utilization. On the other hand, the production of the PV module, and solar cells correspond to the highest contributors to resource utilization because of their copper, tin, and metallization paste requirements.

8.3.4 Contribution analysis for Biosphere Solar PV module (waste treatment strategy 1)

Similar to the results observed for the case of the traditional module - option 1 - the processes of silicon production (single crystal Czochralski process), solar grade silicon production, and PV module production are the largest contributors to the impacts on climate change and particulate matter formation (22.40%, 20.95%, 18.68%, for climate change, and 53.15%, 49.37%, and 58.39% for the latter), whereas the processes of module disassembly, glass, copper, tin, and solar cells reuse reduce the overall environmental impact of the system on the same impact categories. Extremely relevant is the large positive contributions achieved through the reuse of the solar cells, with percentages ranging from -178.65%, -126.45%, and -273.46% for the impacts on climate change, material resource utilization, and particulate matter formation, respectively.

8.4 Sensitivity Analysis

Sensitivity analysis plays a pivotal role in ensuring the reliability of final results and conclusions, by analysing how these are affected by the research assumptions and parameters (De Bruijn et al., 2002). In alignment with the study's assumptions on electricity needs especially for the end-of-life processes, the sensitivity analysis delves into reducing by 10% all electricity inputs to investigate on how such a perturbation may influence the study results. For the sake of simplicity, the sensitivity analysis was conducted – for both alternatives - for all the 12 impact categories exclusively analysing LCIA results and excluding contribution analysis of every single end-of-life waste treatment combination. The results of the sensitivity analysis are available in Appendixes 13, 14, 15, 16, 17, and 18 for the impact categories of climate change, resource use, and particulate matter. A more comprehensive analysis of results on the additional impact categories is available for consultation in the supplementary material.

Overall, the sensitivity analysis results show that reducing all the energy inputs by 10% results in lower impacts on all impact categories for both technologies. In other words, potential life cycle environmental impacts seem to follow the same trend, and hence, results are not disrupted by such perturbation in energy input amounts. For example, the life cycle impact on climate change generated by electricity production through Biosphere Solar technology, generates lower yet still positive environmental impacts for the end-of-life options 1, 2, 4, 5, 7, 8, 10, and 11. This is consistent with the baseline results highlighting a negative environmental impact
for all the waste treatment combinations including solar grade recycling, as opposed to the combinations including solar cell or wafer reuse, which instead reduce the overall impact on climate change rather than contributing to it (by accounting for the avoided burdens of such waste treatment strategies).

A similar consistent trend can be observed for the traditional PV module, for which negative category indicator results are only expressed for the options 1, and 4, which include the reuse of the silicon wafer strategies. Changes in energy requirements also affected human health, through the formation of particulate matter. As a matter of fact, both technologies resulted in lower impacts when electricity was reduced. On the other hand, the energy inputs did not affect the impacts on material resources, which remain unchanged. All in all, results proportionally changed and were not disrupted by the reduction in energy inputs. Therefore, the researcher concludes that results are reliable and aligned with the goal and the scope of the study.

9. Limitations and options for further research

In pursuit of thoroughness and adherence to rigorous scientific methodology, this study identifies several limitations that present opportunities for further investigation in subsequent research:

- Lack of inventory data for bifacial heterojunction photovoltaic cells: Due to the lack of inventory data, information relative to the plasma enhanced chemical vapor deposition (PECVD) was integrated into the inventory data for PERC cell production. This modelling choice was made to account for the fact that heterojunction cells are considered for both PV modules. Additionally, the amount of rear side metal was reduced by 70% to reflect that the PV modules are bifacial. However, such modelling decisions constitute assumptions, and they might not necessarily fully reflect real data for the process of heterojunction bifacial cell production. Consequently, further research should provide life cycle inventories of such type of cells so that these can be integrated in future LCA studies.

• Exclusion of installation and BOS:

As mentioned in the goal and scope definition section, this LCA excludes installation and BOS for difference analysis. Such processes require goods, and energy, and might generate wastes. Therefore, future research aiming at pinpointing the environmental impacts encompassing

those phases should incorporate them for a more comprehensive

analysis. • Limited representativeness of end-of-life strategies:

To analyse the impact of different and more circular end-of-life waste treatment strategies, this study included options such as reuse and recycling that are either not implemented in real life yet, or whose data is not publicly available for analysis. This implied reproducing such processes by means of assumptions, estimations, and by accounting for the avoided burdens approach. These methodological choices might have produced results that might differ from future research relying on possibly more accurate data and estimations. Future research should focus on analysing such processes and collect their corresponding data to improve the quality and consistency of estimations and assumptions.

• Limited representativeness of EVA delamination processes:

This study excluded the option of mechanical delamination. This choice was made because such process commonly results in mixtures of different crushed materials whereas the focus of the analysis was to highlight the benefits of waste treatment scenarios that ensure material efficiency and full components recovery. As mechanical recycling results in crushed mixed materials, this process was considered beyond the scope of the study. However, such decision is not intended to claim any type of environmental superiority of the selected delamination processes with respect to mechanical recycling. Future studies might expand the scope of the analysis by assessing the life cycle environmental impacts of traditional PV modules in which EVA is removed through mechanical delamination.

Additionally, this research assumed simplified activities taking place for both the thermal and chemical delamination process for the EVA removal. The selected quantities for both inflows and outflows were retrieved through estimations and may not be reflective of their real values. Moreover, such activities are expected to be more complex in real life, and they might require additional flows and wastes. Therefore, some environmental or economic flow might have been omitted due to lack of knowledge and data. Upcoming research findings on such processes and their involved exchanges of energy, goods, and environmental flows should be integrated in future related LCAs.

10. Discussion of results

According to the results of this study, and consistently with its assumptions and limitations, the design of the traditional module generates higher potential life cycle environmental impacts than the Biosphere Solar module, across all the waste treatment combinations selected.

With respect to the traditional module, the waste treatment options selected for the solar cells and the EVA delamination method appear crucial in determining the environmental impact of the module across the different impact categories considered. Reusing the silicon wafer generates lower environmental impacts than solar grade recycling, which although is environmentally better than solar cells incineration. The environmental gains are enhanced when the glass components are recycled rather than incinerated, but above all when the EVA encapsulant is thermally delaminated. As a matter of fact, all the waste treatment combinations including chemical delamination of EVA generate higher potential life cycle impacts than the same combinations including thermal delamination.

The results of the contribution analysis pinpointed that almost the totality of the chemical delamination contribution to climate change (33.12% of 34.35% coming from this process) in the waste treatment option 12, stems from the input of toluene. On the other hand, the 8.15% contribution stemming from the thermal delamination process (option 1) is more homogeneously divided among the energy and waste flows. Despite the fact that these results seem to be in line with recent research claiming higher energy requirements and environmental burdens of chemical recycling (Ghahremani et al., 2024; Vaněk et al., 2023), the researcher highlights that the high impact of the chemical delamination process might derive from a potential overestimation of the toluene inflow in the chemical delamination process. Therefore, it is important to interpret these results in line with the assumptions and methodological choices made to reproduce the delamination processes. The assumptions made to calculate the input of solvent required for chemical delamination could be revised in future studies to evaluate
how they affect the overall results of the assessment.

Similarly to the case of the traditional PV module, also for the Biosphere Solar technology the choice of the solar cell waste strategy seems to be decisive in determining the potential life cycle environmental impacts of the module across all the different impact categories. All the waste treatment combinations including the option of reusing the PV solar cell, follow option 1 in terms of lowest environmental impacts. On the contrary, option 6 and 9 – both including solar grade recycling – follow option 12 in terms of highest environmental impacts across the different impact categories considered. Except option 3, 6, 9, and 12, which all include the recycling of solar cells in their waste treatment combinations, all the other options results in negative values and hence indicate a net positive environmental benefit.

All the waste treatment combinations displaying negative category indicator results include the option reuse of the solar cells or the silicon wafer. Their negative values are the consequence of the methodological choice that credit the environmental benefits of avoiding virgin material production to the product. Therefore, by accounting for the so-called avoided burdens, the model led to negative values, which are not to be interpreted as absorbed greenhouse gas emissions from the atmosphere, but rather as avoided emissions that would have been otherwise emitted into the atmosphere if virgin materials were manufactured.

According to the results of the assessment, the electricity estimations made for the waste treatment strategies of both product systems seem to have highly affected the outcome of the study. As explained in the life cycle inventory section, and as thoroughly disclosed in the supplementary material, the electricity inputs stemmed from assumptions. The lower electricity requirements assumed for reuse scenarios resulted in comparatively lower environmental impacts, highlighting the benefits of reuse over recycling and incineration. In contrast, the higher electricity demands for recycling and especially for incineration amplified their environmental burdens.

Furthermore, the results of the contribution analysis convey that the selection of the waste treatment option for the solar cell component has the largest contribution to the overall final impact on the different impact categories, compared to other module components. This can be explained by the more stringent estimation made for electricity requirements of the solar cell component, which was made to reflect research claims on the high value of the silicon components of photovoltaics. For materials like glass, copper, and tin, the electricity selected for the scenarios of reuse, recycling, and incineration corresponded to a given percentage of the electricity needed to produce such components. However, for solar cells, the scenario of solar-grade recovery considered all the electricity requirements – rather than a percentage - necessary to obtain solar cells starting from solar-grade silicon. Similarly, the option of silicon wafer reuse assumed all the electricity requirements necessary to obtain solar cells starting from the silicon wafer, which is less energy-intensive than starting from virgin silicon. Meanwhile, the scenario for solar cell reuse assumed only a symbolic amount of electricity, reflecting the minimal additional energy required to reuse the cells directly without further processing.

Although a larger magnitude in terms of contribution to the different impact categories was expected given the higher energy inputted to produce silicon solar cells, the results of the contribution analysis demonstrated a considerably high difference between contribution of the solar cell waste treatment compared to that of other PV module components. These findings suggest that future studies should prioritize obtaining precise electricity consumption data for various waste management processes to enhance the reliability and accuracy of LCA results.

Therefore, the design changes applied by the start-up Biosphere Solar, namely the removal of the EVA, and the reproduction of the double-glass insulating technology, not only creates opportunities for resource efficiency, but also contribute to overall reduced environmental impacts. To the best of the author knowledge, the results of this study cannot be fully compared to similar LCAs. This is because most of the selected waste treatment combinations selected are not currently implemented in real life (especially for the case of reuse). However, when considering more currently feasible waste strategies (such as option 12 for the traditional module that include chemical delamination, glass, and silicon cell incineration) the results of

this study appear to be consistent and aligned with similar LCA's results. As a matter of fact, producing 1kwh of electricity through the traditional module treated according to option 12, would generate 1.66E-02 kg of CO2-Eq, which is similar to the results presented by Müller (2021), with CO2-Eq emissions ranging from 1.33E-02 to 2.59E-02 kg, and the ones disclosed by IEA PVPS (2017), equal 1.85E−2 kg CO2-Eq when the unit process is scaled to the one of this study.

11. Conclusion

This research investigated the potential life cycle environmental impact of two different single crystalline silicon PV module designs, a traditional glass-glass module with monocrystalline silicon cells, and a glass-glass module with monocrystalline silicon cells designed by the start up Biosphere Solar that removes the EVA encapsulant and that reproduces the double-glass insulating window technology. Additionally, it aimed to pinpoint the end-of-life waste treatment strategies for the modules' various components resulting in lowest and highest potential life cycle environmental impacts. Both modules were assumed to be produced in China, to operate in the Netherlands, and to be treated as waste in Germany.

According to the results of this study, the design of the traditional module generates higher potential life cycle environmental impacts than the Biosphere Solar module, regardless the waste treatment combinations selected. Results demonstrated that lower, if not positive, environmental impacts, across all the different impact categories considered, are achieved when circular end-of-life solutions are included in the waste treatments of both PV module designs. The lowest environmental impacts are generated by producing electricity through Biosphere Solar technology, when this is eventually treated as a waste in a way that combines glass, copper, tin, and solar cell reuse. Similarly, although reuse is not always possible for the case of a traditional technology (due to EVA presence), a waste treatment scenario comprising thermal delamination, glass, copper, and tin recycling, and silicon wafer reuse, would generate lowest environmental impacts compared to all the other waste treatment combinations included in the study.

Waste treatment options 12 represent the combinations generating highest potential life cycle environmental impacts for both technologies. This would encompass processes such as chemical delamination, glass incineration, and solar cell incineration, for the traditional technology, and glass, copper, tin, and solar grade recycling for Biosphere Solar PV module. Therefore, answering the first and second research question, end-of-life options 1 and 12 correspond to the environmentally best and worst waste strategies for both technologies.

With respect to the research question 3, when comparing the potential life cycle environmental impacts of the two alternatives, Biosphere Solar technology displayed lower environmental impacts across all the impact categories than the traditional technology, for both options 1 and 12, demonstrating that modular design and end-of-life treatment processes significantly impact the overall environmental performance of photovoltaics. Circular end-of-life strategies -reuse and recycling - play a crucial role in reducing environmental impacts, especially when they are preferred to incineration. There is hence the need to establish nuanced waste management approaches and combinations that optimize materials recovery and avoid the production of virgin material. As demonstrated by the start-up Biosphere Solar, this could be achieved through improvements in module designs. Therefore, integrating the principles of circular economy starting from a product design stage, would allow for reuse or recycling opportunities. This in turn, would contribute to enhanced material efficiency and hence to a swift and sustainable transition to renewable energy systems.

Appendix

1. Possible end-of-life treatment options for Biosphere Solar PV module
2. Possible end-of-life treatment options for Traditional PV module
3. LCIA results for Biosphere Solar twelve different end-of-life treatment combinations.
4. LCIA results for traditional PV model twelve different end-of-life treatment combinations.
5. LCIA results for material resources, traditional PV module.

6. LCIA results for particulate matter formation, traditional PV module. 7. LCIA results for

material resources, Biosphere Solar PV module.

8. LCIA results for particulate matter, Biosphere Solar PV module.
9. Traditional PV module treated as waste according to option 12 – process contribution analysis

10. Biosphere Solar module treated as waste according to option 12 – process contribution analysis
11. Traditional PV module treated as waste according to option 1 – process contribution analysis

12. Biosphere Solar module treated as waste according to option 1 – process contribution analysis
13. Sensitivity analysis results, impact on climate change, Biosphere Solar PV module

14. Sensitivity analysis results, impact on climate change, Traditional PV

module *Figure 5. Sensitivity analysis results, impact on climate change, traditional PV module*

15. Sensitivity analysis results, impact on resource use, Biosphere Solar PV

module 16. Sensitivity analysis results, impact on resource use, traditional PV module

17. Sensitivity analysis results, impact on particulate matter formation, Biosphere Solar PV module

18. Sensitivity analysis results, impact on particulate matter formation, traditional PV module

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