COMBINING CIRULARITY AND ENVIRONMENTAL METRICS TO GUIDE DEVELOPMENT IN PV

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ABSTRACT: A product made from virgin raw materials that ends up in a landfill presents a linear supply chain model. Today's photovoltaic (PV) industry is still largely based on this model. With the increasing volume of production, the raw materials required for it, and consequently the volume of waste, the application of circular economy principles in the PV sector can significantly increase its environmental efficiency. This study analyzes the impact of circularity on the supply chain of PV systems, using the example of silicon used for PV wafer production. Four scenarios based on different technological parameters and circular economy principles are defined. Their evaluation is carried out by the methodologies of Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA). The State-of-art case of the PV polysilicon supply chain corresponds to the MCI score of 0.54. Closed-loop circularity solutions provide the MCI score of 0.80 presenting the potential for a circular economy approach in the field. LCA results covering 16 impact categories show the reduction of environmental impact by 12% with improved circularity and 46% by technological development. The results present the benefits of potential circularity options within the supply chain as well as the impact of technological development on the polysilicon demand.
Keywords: Circularity, Life Cycle Assessment, Polysilicon, Metrics

1 INTRODUCTION

In order to meet long-term climate change targets, intensive photovoltaic (PV) deployment is needed in the future [1]. Large amounts of materials are required to achieve this goal [2]. Possible options to meet this demand are to use virgin materials or to implement circular economy (CE) approaches to the industry. Transforming material flows to the closed loop within production steps as well as after the product's lifetime is a way to implement CE principles to the market. With the increasing production volume, the required raw materials, and the associated amount of waste, the circularity in the PV sector becomes a critical topic.

The application of circular economy approaches in photovoltaics have been analyzed in terms of environmental, technological, economic, and legislative arguments [3-5]. However, a research gap could be identified in the quantitative assessment for circularity in PV. The circular model is based on three principles: design out waste and pollution, keep products and materials in use, regenerate natural systems [6]. As these principles are represented by various parameters the need for universal metric remains. Material Circularity Indicator (MCI) includes the parameters related to the circularity and provides the single score result [6]. The metric provides a chance to estimate various CE scenarios and allows stakeholders to understand how far the products are on transitioning from a linear to a circular supply chain. Combination with additional risk indicators allows to understand the significance of circularity in environmental, economic or social contexts. More circular material flows on selected level does not necessarily lead to more environmental-friendly solutions. The interaction between circularity and life-cycle-based environmental indicators has been discussed in the literature [7,8]. Still, there is no widely-accepted universal metric combining circularity and environmental performances.

So far, the circularity in the PV sector, both for the module as a whole and its materials, has not been assessed through the herein used dedicated circularity indicator. This study aims to assess circularity of polysilicon in the PV supply chain and to measure how the implementation of circular solutions influences the performance indicators. Complementary, Life Cycle Assessment (LCA) is used for the estimation of impacts on the most relevant environmental impact categories. Therefore, this study aims to present an assessment example that can be used as an aid to decision-makers to guide technology development.

2 APPROACH

The study is carried out testing Material Circularity Indicator for circular economy approach and its combined utilization with Life Cycle Assessment for environmental impact of polysilicon under consideration of four scenarios.

The functional unit (FU) used in the study is 1 MWh of electricity produced by a PERC p-type mono-Si PV module under global average irradiation conditions.

2.1 Scenarios

Four scenarios based on technology and circularity are applied in the research. Two technological pathways are created: State-of-art PERC and 2032 ITRPV projection. The data of the IEA PVPS [9] Life Cycle Inventories provide detailed bills of materials for all production steps of PV module: metallurgical-grade silicon, Czochralski single crystal, silicon wafer, photovoltaic cell, and module production.

The technological development is carried out on expected trends for photovoltaics

- The data for 2021 is used to describe the product's specification in the State-of-art PERC scenario.
- In the case of the 2032 ITRPV projection it is assumed that improvements are implemented in the wafering process by reducing the kerf loss content and wafer thickness, as well as in the increase of the module efficiency. Values for these parameters are anticipated for the year 2032 by the International Technology Roadmap for Photovoltaic (ITRPV) [10]. A longer lifetime of the product is assumed.

Two circularity options are applied in the research. Waste treatment options are designed based on technological, economic, and legislative conditions working in the field.

- The option "Business-as-usual" represents the current situation in the industry which is based on economic reasons and legislation requirements. According to The Waste of Electrical and Electronic Equipment (WEEE) [11] silicon treatment from End-of-life (EOL) photovoltaic modules is not mandatory and therefore usually not implemented in recycling processes due to lack of economic reasons.
- The "Closed-loop" circularity option represents an example of improved Si recovery, which allows silicon to be used again in a circular way for new PV polysilicon production. Kerf loss recovery to metallurgical grade silicon is possible by methods of thermal plasma, carbothermic reduction or inductive melting (recycling efficiency – 65%) [12]. A selected EOL technology – FRELP – Full Recovery End of Life Photovoltaic [13] provides the recovery of silicon from solar cells with a purity of metallurgical grade silicon as well (recycling efficiency – 95%).

Other parameters and assumptions related to material flows and losses (production yields, collection rates, etc.) are assumed constant among the different scenarios.

2.2 Methodologies

The methodology of Material Circularity Indicator was introduced by the Ellen MacArthur Foundation. The indicator is essentially constructed from a combination of three product characteristics [6]:

1. mass V of virgin raw material used in manufacture
2. mass W of unrecoverable waste that is attributed to the product (W_0 – uncollected waste, W_C – waste generated in the recycling process; W_F – waste generated to produce any recycled content to use as a feedstock)
3. utility factor X that accounts for the length and intensity of the product's use.

Based on material flows the Linear Flow Index (*LFI*) can be computed. *LFI* measures the proportion of material flowing in a linear fashion. The index takes a value between 0 and 1, where 0 is completely restorative flow and 1 is a completely linear flow [6].

The *LFI* is calculated as follows:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{1}$$

The second parameter in the MCI is the utility X of a material or product. The utility X is derived from the lifetime and functional units of a product compared to an industry-average product of the same type.

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right) \tag{2}$$

The Material Circularity Indicator can be defined by considering the *LFI* of the product and a factor $F(X)$, built as a function F of X that determines the influence of the product's utility on its MCI. The equation used to calculate the MCI of a product is

$$MCI^{*}_{P} = 1 - LFI \cdot F(X) \tag{3}$$

Where F takes the form:

$$F(X) = \frac{0.9}{X} \tag{4}$$

MCI takes, by convention, the value 0.1 for a fully linear product (i.e., $LFI = 1$) whose utility equals the industry average (i.e., $X = 1$), while MCI value of 1 presents totally circular product [6].

In analogy to the MCI calculation, the goal of the Life Cycle Assessment is to investigate the environmental impacts that can be allocated to the silicon in a p-type mono-Si PV module. The LCA is conducted from cradle to gate, including the process steps from raw material extraction to the finished PV module. The chosen system model is cut-off. Here, recycled materials are assumed to be burden-free, as their impacts are allocated to their previous life-cycle. Any materials in the PV module other than silicon are excluded in this analysis. Auxiliaries such as electricity and heat are included on a weight-ratio-basis. Any balance-of-system components are out of scope in this study. The location of the production is assumed to be China.

As recommended in the Product Environmental Footprint Category Rules (PEFCR) the chosen impact assessment methodology is EF3.0 [14]. Additionally, the impact category *Climate Change* is investigated in more detail, as it is one of the most robust indicators and has the highest contribution to the final single score result.

3 RESULTS

3.1 Material Circularity Indicator

The resulting values for the parameters of MCI (FU = 1 MWh) are given in Table I.

The relatively high MCI result of 0.54 for the scenario State-of-art PERC/Business-as-usual case is mainly due to the reuse of the ingots' sidewall slabs, tails, and tops that are cut-off to form the polysilicon brick from an ingot. These pieces are remelted into Cz ingot and, due to high collection and internal recycling rates, have a significant impact on the MCI result. Under Closed-loop circularity, both the kerf loss and silicon from EOL waste are recovered as metallurgical grade silicon. Using it for PV polysilicon production significantly reduces the demand for virgin material.

Table I: Results of MCI and its parameters

			MATERIAL FLOW PARAMETERS			**UTILITY PARAMETERS**		
Scenario	Technological pathway	Circularity option	Virgin materials (g/MWh)	Unrecoverable waste (g/MWh)	Linear Flow Index	Lifetime (years)	Utility	MCI
Scenario 1 (S1)	State-of-art PERC	Business-as-usual	86.6	65.1	0.52	25/25	1	0.54
Scenario 2 (S2)		Closed-loop	38.8	27.1	0.22	25/25	1	0.80
Scenario 3 (S3)	2032 ITRPV projection	Business-as-usual	48.0	37.1	0.52	35/25	1.4	0.67
Scenario 4 (S4)		Closed-loop	21.4	15.1	0.22	35/25	1.4	0.86

As mentioned above the Linear Flow Index presents how linear the material flows are. The LFI result for Business-as-usual circularity is 0.52 both for State-of-art PERC and 2032 ITRPV projection. Production efficiency remains the same in most of the processes despite the technological path. Linear Flow Index for Closed-loop option amounts to 0.22, corresponding to high circularity. Still, there is a potential for improvement in the waste treatment related to low recycling efficiency and collection rates.

The second component that influences the MCI score is product utility. The 2032 ITRPV projection scenario declares a longer lifetime (35 years) which increases the Utility (X) to 1.4. On the improved technology case LFI scores remain the same, therefore only the higher Utility ratio leads to higher MCI results: 0.54 to 0.67 and 0.80 to 0.86 on Business-as-usual and Closed-loop options, respectively. A longer lifetime satisfies one of three circular economy principles – to keep products or materials in use. Some PV manufacturers already guarantee longer lifetimes for their products than 25 years.

The methodology of the Material Circularity Indicator allows to account for the mass of virgin materials and unrecoverable waste associated with a product. The values in Table 1 are expressed by the product of polysilicon. The effect to these parameters of technology or circularity improvement can be compared. A reduction achieved in the case of the 2032 ITRPV projection is 44-45% for the aforementioned parameters in comparison to State-of-art PERC. While Closed-loop circularity lessens the mass for virgin materials by 55% and 59% for unrecoverable waste in comparison to Business-as-usual circularity.

3.2 Life Cycle Assessment

Figure 1 presents the single score results per scenario (FU = 1 MWh, Method – EF3.0).

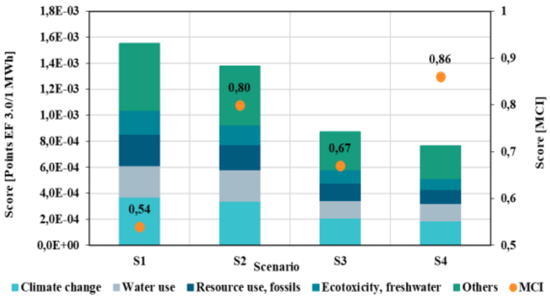

Figure 1. Normalized and weighted single score results (EF3.0) of environmental impacts by category

Further, the contributions by the different impact categories are visualized. Scenario 1 causes the largest environmental impact in this comparison, followed by scenario 2, 3 and 4, in that order. The single score for scenario 4 is about 51% lower than for scenario 1. The improved circularity decreases the environmental impacts by around 12%. At least two thirds of the single score impacts in all scenarios are due to the *Climate Change*, *Water use*, *Resource use, fossils*, and *Ecotoxicity, freshwater* categories. The results indicate, that the technological development has a more significant influence on the end result, reducing the impacts by around 46% regardless of the circularity option. The 2032 ITRPV Projection scenarios ensure higher built-in material efficiencies, which are directly related to lower production volumes. This has a larger effect on the single score result than the reduction of virgin material processing.

The cause of the specific impact can be further investigated in the category of *Climate Change* (midpoint) for all scenarios. The carbon footprint of the silicon in the PV module for 1 MWh of produced electricity is 14.25 kg CO_2 eq., 13.06 kg CO_2 eq., 8.02 kg CO_2 eq., and 7.28 kg CO_2 eq. for scenarios 1, 2, 3, and 4, respectively. Half of these impacts originate from the silicon production mix. This includes all impacts from the raw material extraction to the single crystal production in the Cz ingot pulling. The production location is China. Most of the impacts caused in the silicon production mix can be traced back to the electricity consumption in the supply chain, as it is an energy intensive process and the Chinese electricity mix relies heavily on coal-fired power plants.

The LCA results indicate that the State-of-art PERC/Business-as-usual scenario (S1) causes the most environmental impacts in this comparison. The silicon production and the electricity use along the production line are the main sources of impacts in all scenarios. The reduction in the energy and silicon consumption across the scenarios has therefore a substantial influence on the respective LCA results. Scenarios 2 and 3 cause less environmental impacts per MWh than scenario 1. When comparing scenarios 2 and 3, it becomes apparent, that technological improvement with Business-as-usual circularity outperforms the State-of-art PERC with improved circularity. The increase in electricity production due to the elongated lifetime has a greater impact on the impacts per MWh than the Closed-loop circularity. In scenario 4, where both improvements are combined, the environmental impacts are reduced by about 51% compared to the original design in scenario 1.

The improvements in the *Climate change* impact category among the scenarios (from 1 to 4) is mostly due to the reduced electricity consumption as well as the lower demand for silicon. As shown in Figure 1, the *Water use* category has also a high impact on the overall single score results. Also, the impacts in this category are greatly influenced by the reduction in silicon demand, across the four investigated scenarios. The Cz ingot pulling in the silicon production is the main cause of water consumption in the production of a PV module. While in scenario 1, the water use amounted to 32.8 m^3 depriv./MWh, this is reduced by the scenario 4 to 18 m^3 depriv./MWh.

4 DISCUSSION

The methodologies of MCI and LCA can be discussed on some critical arguments. One of the main CE goals is to lessen inputs. However, the MCI as a metric is based on a mass proportion of waste and recycled material. It means that high collection and recovery rates of wastes within production steps increase the overall MCI value of the product. In our case Poly-Si ingots are cut-off to form the shape of the wafers. However, cut pieces are remelted again to Cz crystal. Following the methodology, these steps significantly increase the MCI score. Nevertheless, it contradicts the idea of using fewer resources [15]. The chance to increase circularity by creating not relevant waste and reusing it could be an example of so-called “circular washing". The strategy used by companies to present goods as produced in a circular economy style.

The MCI analysis includes a cradle to grave approach, while the LCA is based on a cradle to gate analysis. In the LCA the recycled content is included, however the emissions of possible recycling processes are not, due to a lack of data. Further, the LCI has been adjusted to fit the MCI scope of analysis more closely, so that only the impacts allocated to the silicon within the PV module are included. Any other materials (for example the frame, or metallization pastes) that are part of a PV module have not been investigated. Auxiliaries, such as electricity, heat and transport have been included based on a weight-ratio, meaning that the weight fraction that the silicon has in a PV module, cell or wafer was applied to calculate the allocated auxiliary inputs. This entails uncertainty and can influence the end result. Finally, the normalization and weighting of the characterized results introduces additional uncertainty. However, to achieve a single score for the respective scenarios and make them more easily comparable, this step was taken.

5 CONCLUSION

The results showed that the State-of-art case of the PV polysilicon supply chain corresponds to the MCI score of 0.54. The higher-than-expected result is achieved mainly by internal recycling. Improved circularity with kerf loss and EOL waste recovery on the closed-loop model significantly increase the overall MCI value up to 0.80. The implementation of Closed-loop circularity reduces the need for virgin material by up to 55% and up to 59% for unrecoverable waste in comparison to Business-as-usual circularity. The effect of improved utility on the aforementioned parameters was not so significant. However, the evaluation by Life Cycle Assessment methodology showed that improved utility causes lower environmental impact, since it significantly reduces the volume of production. Extended lifetime contributed to decreased environmental impacts, too.

This paper contributes to research evaluating circular economy approaches in the PV industry. The results highlighted the benefit of joining metrics for circularity and environmental assessment. Interaction between them can be interpreted in the context of sustainability as guidance for development in photovoltaics.

ACKNOWLEDGMENT

Aistis Rapolas Zubas would like to thank Deutsche Bundesstiftung Umwelt (DBU) for funding the research at Fraunhofer ISE through the programme "Fellowships for university graduates from Central and Eastern Europe".

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