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INSIGHTS INTO CIRCULAR MATERIAL AND WASTE FLOWS FROM C-SI PV INDUSTRY

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ABSTRACT: A material flow model for the production of Bifacial Selective Emitter 60-cell p-type Cz PERC (Passivated Emitter and Rear Contacted) glass-backsheet modules with aluminium frame was built. The selected module represents mature technologies in the PV industry and their manufacturing is considered to take place in China in a production cluster with an annual module capacity of 5 GWp. In a first step, data acquisition and validation for wafer, cell, and module fabs took place. The data were used to generate the reference system lifecycle inventories (LCI) and extended waste databases for the reference wafers, cells, and modules. A set of potential circularity actions, such as the vertical integration of the operations and waste revalorisation strategies, had been proposed and their environmental performance and cost assessed by means of a life cycle assessment (LCA) and a total cost of ownership (TCO). Our results show that 87% of the waste can be reduced and revalorised, this represents a circular flow of raw materials of 18,756 Mg per year from a 5 GWp PV module production cluster. Environmental impact reductions of 0.6 to 2.3% are estimated for different impact categories. We also estimate a cost reduction potential of 2.59% from total module costs.

Keywords: photovoltaics/ revalorized waste/ circular production/ life cycle assessment/ total cost of ownership

1 INTRODUCTION

1.1 Motivation

Photovoltaics (PV) have emerged as the backbone of the global energy transition. An expansion from the current 707 GWp PV capacity up to 63 TWp by 2050 is deemed to be both needed to comply with a 1.5°C scenario and viable from a technical and economic perspective [1]. This massive deployment and current developments on legislation of industrial sites requires from PV manufacturers to achieve exemplary sustainability. Resource consumption patterns are at the core of said sustainability, as they can affect the environmental, social, and economic performances of a product [2,3]. Hence, there is a strong need to make today's production systems more efficient. Waste flows must further be minimized and converted into streams of valuable materials, for not to be lost and to end up on landfills.

Circularity strategies in PV manufacturing are essential as they can considerably improve the sustainability of PV modules, already in the short term. Assessing the potential of such strategies requires a detailed analysis of material flows (MFA) to understand each process step, resources requirements, material losses and waste handling. Which this paper proposes to lay out through bottom-up modelling.

The generation of a broad bill of materials to derive life cycle inventories and extended waste database allows the assessment of the system circularity from many perspectives.

1.2 Methods

First, current material and solid waste flows (MFA model) for a reference production chain are identified and quantified for the production of monocrystalline silicon (c-Si) ingots and wafers, passivated emitter rear contact (PERC) solar cells and PV modules for an annual capacity of 5 GWp located in China.

By generating the MFA, potential optimizations, e.g., vertical integration, waste revalorisation, as well as reduction of wafer breakage, material loss, packaging, energy and transportation can be identified. Second, the circularity strategies cost and environmental performances are assessed by means of a total cost of ownership (TCO) and a life cycle assessment (LCA). Overall, the discussion over the advantages, disadvantages and challenges associated with each concrete optimization strategy can be of interest for researchers and industrials alike in progressing towards circular PV factories.

1.2.1 MFA and TCO

The MFA and TCO models are bottom-up calculated with the following hierarchy levels:

- Level 1: Individual equipment.
- Level 2: Production line and supply infrastructure.
- Level 3: Total factory including building requirements.

The MFA and TCO are calculated with Fraunhofer ISE technology and cost assessment model Scost [4] which follows mainly the standards SEMI E35 [5] and E10 [6] for cost of ownership and equipment utilization calculation, respectively. The costs for Process Consumables, Utilities and Waste Disposal are considered separately, instead of the aggregated Consumables cost component in SEMI E35. The Process Consumables include raw materials for the production processes. The Utilities cost considers electricity, process exhaust air, process cooling water and compressed dry air. The Waste Disposal category includes the costs of gas scrubbers and solid waste and wastewater disposal and treatment. The category Maintenance Parts includes costs of parts repair and replacement. Labour costs for maintenance and operation are included in the Labour cost category.

1.2.2 LCA

To give an estimate on the reduction potential of environmental impact of the PV module production and proposed reduction measures of production wastes, an

LCA was implemented following the ISO14040 [7] and 14044 [8] standards. The LCA is based on the described MFA model and implemented using the GaBi software and its databases (version CUP 2022_1) [9]. The Life Cycle Impact Assessment (LCIA) is based on the suggested impact method set of the EU Environmental Footprint, Version 3.0 (EF3.0) [10].

The defined functional unit and reference flow for the LCA is the production of 1 m^2 PV module with respective technical specifications summarized in Table I. The system boundary is cradle-to-gate, considering the impacts along the entire value chain until the PV module factory gate.

The considered reference location of the PV module production is China, which is represented in the LCA model by using country specific energy generation mixes, materials, and process auxiliaries where available. In case that no region-specific dataset is available in the GaBi database content, datasets with deviating regional references were used as a proxy (e.g., datasets referring to EU-28 productions). This is mainly the case for the chemical use in the different process steps of the PV module production.

To enable an estimation of the reduction potential of environmental impacts resulting from the analysed strategies for waste reduction and waste revalorization, an additional LCA model was created that allows the analysis of specific waste streams and waste treatment options. Finally, the LCIA results of this waste specific model are put into relation to the reference module production.

2 INVESTIGATED PV PRODUCTION CHAIN AND WASTE MANAGEMENT

2.1 Investigated PV production chain

The full production chain of the Bifacial Selective Emitter 60-cell p-type Cz PERC glass and backsheet modules with aluminium frame reference product is split into three fabs, the product specifications are shown in Table I.

Table I: Products specifications per factory

Wafers		
Crystallization Type		**Cz**
Base Doping		p-Type
Thickness	µm	170
Wafer Edge Length	mm	156.75
Wafer Mass	**g**	**9.70**
Cells		
Ø Cell Power (Pmpp)	**5.37**	**Wp**
Cell Mass	**g**	**9.19**
Modules		
Cell per Module	**60**	**Cells**
Ø Module Power (Pmpp)	**316.80**	**Wp**
Module Area	**m^2**	**1.598**
Module Mass	**kg**	**18.72**

2.1.1 Ingot and wafer fab

The main flow is the one of polysilicon input to the crystallization process and its subsequent processing through the cutting and cleaning steps from ingots to rods, from rods to bricks and from bricks to wafers. The polysilicon input is composed of a virgin material feed accounting for 56% of the total flow and the polysilicon reclaim feed providing 44% of the input flow. The reclaimed polysilicon is integrated by rods sidewalls slabs, misprocessed workpieces, ingot tails and tops. In order to reclaim and reuse these workpieces for the polysilicon feed for the crystallization process, the pieces are crushed and etched in chemical baths. About 69% of the virgin polysilicon feed is transformed into wafers, the rest 31% ends up as silicon kerf loss in the industrial wastewater. With press filtration it is possible to recover 3,890 Mg of solids per year for the considered module annual production capacity of 5 GWp. From the silicon crusher we estimate a recovery potential of 237 Mg per year. The second most relevant material flow is the one of the quartz crucibles, which are used for the crystallization process; after three cycles of crystallization, they are removed with the residual silicon pot scrap from the pullers and disposed of. The silicon pot scrap and wasted crucibles sum up to 1,737 Mg per year.

2.1.2 Cell fab

In the cell factory the as-cut wafers are further processed in chemical baths to remove the sawing damages and to texturize their surface to increase the absorption of sunlight. After the diffusion process of the phosphor emitter, a phosphosilicate glass layer (PSG) is formed around the wafers, by means of chemical baths. The emitter layer is removed from one side of the wafers and the PSG is removed from both sides of the wafers. The texturized and dopped wafers are thermally oxidized and then rear passivated with two layers, one of 15 nm of aluminium oxide (Al_2O_3) and a second layer of 70 nm of silicon nitride (Si_3N_4). Afterwards, the Anti-Reflective coating is built on the front side with one layer of 85 nm of Si_3N_4. The contact points to the bulk structure are opened by lasers and then the metallic contacts are screen printed at the back and front sides, 17 g of metallic pastes are used per square meter of cells. For the annual 5 GWp module production capacity of PV modules, 193 Mg of non-metallized cell scrap and 186 Mg of metallized cell scrap are generated yearly.

2.1.3 Module fab

The main raw materials weight shares for the production of the reference PV module are 68.6% for the glass layer, 14.3% for the aluminium frame, 6.8% for the encapsulant (EVA) and 4.3% for the backsheet. Solar cells only have a weight share of 3.2% of the total raw materials required to produce a PV module. Module packaging accounts for almost 17% of the weight of packaged PV modules. From the waste perspective we estimate a generation of 0.48 kg of solid waste per square meter of produced PV module, this is mainly composed of wood, glass, and plastic waste. In terms of the annual 5 GWp module production capacity -eq. to 25.500.741 m^2 of PV modules- the generated mix waste in the module factory sums up to 12,268 Mg per year.

From an overall perspective, it can be stated that the main material flows occurring along the value chain from polysilicon to PV modules are the ones of glass, aluminium, module packaging materials, encapsulant and backsheet. From the waste generation perspective, we estimate a total solid mix waste flow of 21,348 Mg per year. The dominant waste partitions are composed of wood, silicon kerf, glass, and plastics. Strategies into reducing the material intensity of the industry are discussed in the section 3 of this paper.

2.1.4 Reference PV module cost

We estimate a TCO of 88.6 €/module. In terms of square meter of PV module, the TCO is 55.45 € and in terms of power units 0.28 €/Wp. This cost is just 20% higher than recent average prices shown in the PV market [11]. Our cost estimation seems plausible as we calculate our reference for the older wafer format M2.

In **Fehler! Verweisquelle konnte nicht gefunden werden.** we present the TCO distribution per cost categories. It is possible to appreciate that raw materials costs have a share of almost 70% of the total costs per PV module —polysilicon alone drives close to 30% of the TCO. These facts make very clear that scrap generation, wafer and cell breakage rates should be under control along the value chain. The category "Waste disposal" is composed of wastewater and exhaust treatment costs and solid waste disposal with a mix waste strategy -assumed as reference-. The "Yield loss" category entails the associated losses of raw materials, wafer, and cells breakage along the production chain, it is calculated for an efficient operation setting.

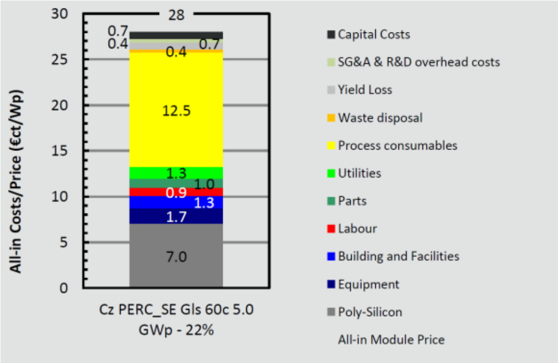

Figure 1: PV module cost per cost categories (reference)

2.2 Waste management

Based on the data of the material flow model, an extended waste database was created. The purpose of this database was to collect information about the individual solid wastes and to identify the possible hotspots for circular economy.

2.2.1 Legal framework

In addition to concrete requirements from specific waste legislation, depending on the production site, requirements from neighbouring regulations, e.g., construction, occupational health and safety, etc., have to be included in the planning of a production plant with regard to the management of waste and by-products generated. Within the scope of the present project, Germany was considered as a representative example of a European location. Since the reference model refers to the location China, the corresponding legislation was also taken into account as far as identifiable.

The most relevant European regulations are the WEEE [12], Waste Framework Directive [13] and the CLP Regulation [14], which must be transposed into national law by the member states. These are authoritative for local operations.

According to [15] the waste management of China is inspired by the organization of waste management in Europe. Ministries provide the framework (programs, laws, regulations, etc.), while the provincial and municipal governments are responsible for implementation. Nationally, the Ministry of Environmental Protection and the Department of Soil Environmental Management are responsible for electronic products and waste. Relevant laws include Environmental Protection Law, Regulations for the Collection, Transportation and Recycling of Municipal Waste, Law for the Promotion of Clean Production of the PRC, Law for the Promotion of Circular Economy and currently the 13th Five-Year Plan: Municipal Plan for the Safe Management of Municipal Waste. For the management of waste electrical and electronic equipment, a Guideline of Waste Electrical and Electronical Products Standardization Dismantling Operations and Product Management exists [15].

2.2.2 Approach to database

The database created is based on a waste register for commercial enterprises, which was expanded to include project-specific aspects. Identified wastes were grouped into waste categories (paper, metals, glass, ...). Subsequently, the wastes were described by composition (waste description) and extended by information on the waste-generating link within the production chain (waste origin). In addition, the waste register contains information on recycling and circularity. Another section provides information on hazardous and/or critical materials or conflict minerals. Beyond these aspects, the database can be extended, for example, by plant-specific key figures.

According to [15], collection and plant structure would show significant differences to the situation in Europe. The scope of documentation and definitions also differ. For example, according to [15], disposal in secured landfills is considered as treatment of waste and the main part of collected waste is seen as to be landfilled. Recyclable materials are generally collected and recycled by the so-called informal sector.

For the reference analysis, it was defined that the remaining waste from production is handed over to an approved disposal company and deposited in a secure landfill.

In order to estimate the potential, the waste volumes were divided into the disposal options "recycling", "energy recovery" and "disposal" on the basis of waste-specific quotas. The quotas are largely based on the distribution of material flows in Europe [16]. For specific wastes, in particular wastes containing silicon, the distribution was estimated based on the experience of the project participants.

3 POTENTIAL IMPROVEMENTS IN TERMS OF CIRCULARITY

3.1 Vertical integration

The occurring waste flows, including packaging and residues, were classified by type and their value assessed to suggest their treatment in terms of material and energy recovery potential.

We use the term vertical integration for stating that the manufacturing of multiple products in the production chain takes place at the same site. The boundary of our analysis starts with the reception and storage of polysilicon, glass, metallic pastes, diamond wire, polyurethane beams, quartz crucibles, backsheets, ribbons, solder, chemicals, and gases and end up with the production of the reference PV modules.

By concentrating the individual fabrications at one location, the packaging demands of the intermediate products are lower compared with external transports. The reduced number of reloading operations also reduce the risk of breakage. Therefore, the losses are minimized and fewer silicon ingots, wafers, etc., need to be produced. Furthermore, less paste is needed and there is less effluent and waste to be treated. Vertical integration can achieve a 11% reduction in the amount of waste, which accounts for 2,205 Mg per year. The demand for raw silicon is reduced by 75 Mg per year for the 5 GWp PV module cluster.

From the cost perspective, our results show that the Vertical Integration of the factories enables a total cost reduction per module of almost 1%.

3.2 Revalorized waste

Some outputs or waste fractions have a certain commercial value which should be realized. Options for recycling of kerf, quartz, graphite, defective or broken cells, polymers, glass, metal, paper, plastic, and wood are available in varying quantities and qualities depending on location of the plant. For example, Si-kerf can be reused for the production of Si ingots after processing and purification. The Si-kerf can also be used for the production of silicon nitride (Si_4N_3) crucibles or SiC. A recovery of solar cells requires a complete separation of the individual layer metallization layers. Thermoplastic polymers can be melted down, cleaned and reintroduced to the market as high-quality recyclates. For the nowadays frequently used thermoset materials no relevant recycling route (e.g., EVA) has been established yet. The glass is mainly used for the production of glass fibres or foam glass.

The metals can be automatically separated from the mixture with the cullet by metal separators. Aluminium from the frames, for example, can be reused by melting it down. Wastepaper is used to a very large extent in the manufacturing of new goods. Waste wood can be used in the furniture industry but is predominantly processed into fuel.

To estimate the potential of a consequent solid waste separation in different fractions and an available treatment and recycling plant structure like in Europe is assumed.

The occurring waste flows, including packaging and residues, were classified by type and their value assessed to suggest their treatment in terms of material recovery, energetic recovery, and waste disposal. The results also consider the implementation of a reusable wood pallet system between factories, as shown in Figure 2.

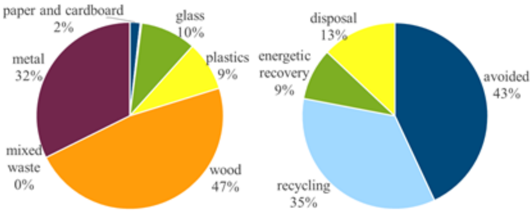

Figure 2: Poly-Si to PV modules waste flows (left side) with recycling options (right side) using reusable pallets

Out of a total cost reduction per module of 1.65%, 69% is gained due to the establishment of reusable pallet system -most of it for the glass and module transportation, 18% is contributed by the silicon waste recycling for use as ferrosilicon.

The amount of waste to be disposed of could be reduced by approx. 43% compared to the reference scenario, which represents 9,112 Mg per year. By allowing a plant for recycling and energy recovery and using reusable pallets instead of disposable pallets, 35% of the generated reference waste could be considered as recycled, 9% as energy recovered. The rest would have to be disposed of in a landfill.

3.3 LCA implementation

3.3.1 Assumptions and modelling choices for waste treatment options

Since no processes are available to represent the specific characteristics of waste treatment options for PV materials, such as silicon wastes from kerf loss, solar cells, or filtered metal dust, assumptions had to be made for the recycling, thermal recovery, and disposal of waste materials streams by using existing end-of-life treatment datasets of the GaBi database content. Due to limited availability of China (CN) specific datasets, waste treatment processes referring to the EU-28 region were chosen as a proxy. These datasets allow appropriate estimates by providing average data for the end-of-life treatments of conventional industrial materials, such as pulp and paper products, wood, plastics, copper, aluminium, and ferrous metals. As these necessary assumptions are associated with corresponding uncertainties, not all impact categories of the EF3.0 could be evaluated, especially for those that are strongly influenced by very specific process emissions or the regional conditions. For a sound evaluation, precise process and emission data are required to allow a reliable classification of the environmental impacts, e.g., in impact categories related to eco- or human toxicity.

The baseline for the evaluation, as defined in the reference scenario, considers that all production wastes streams are disposed of on landfills. For the revalorized waste scenarios, potential environmental impacts caused by landfilling and thermal treatment of wastes in waste incineration plants are taken into account. Due to the fact that some recycling options, especially for Si-wastes, are based on rough assumptions, we chose a cut-off approach for all recycled materials and energy recovery processes.

The vertical integration measures are evaluated with and without the revalorized waste scenario options, resulting in four separate LCA scenarios.

3.3.2 LCA results

Figure 3 presents the environmental impact reduction potentials of the investigated waste reduction strategies in relation to the reference PV module production on module level (represented by the 0% line).

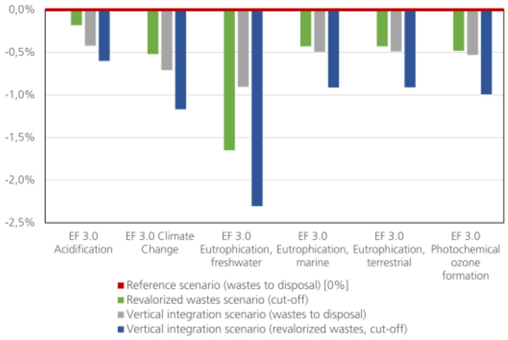

Figure 3: Environmental impact reduction potentials of investigated solid waste reduction and treatment strategies in relation to the reference PV module production (module level)

The vertically integrated production reflects savings related to the avoided production of packaging materials, such as paper and plastics as well as slightly reduced losses to wafer and cell breakage during transportation. Reductions on the production side of the revalorized waste include the change from one-way pallets to reusable wood pallets.

The environmental effect of avoiding use of packaging materials in a vertically integrated production leads to higher reductions in most of the investigated impact categories compared to the revalorized waste scenario, when potential environmental benefits for material recycling and thermal recovery are not taken into account (due to the cut-off approach). The revalorized waste scenario shows a higher reduction potential in the freshwater eutrophication potential, mainly resulting from the reduction of plastic wastes put on landfills.

Since the waste reduction strategies of the vertical integration and the revalorized wastes scenarios can be combined, the highest savings of environmental impacts are reached with this scenario in all investigated impact categories.

4 CONCLUSIONS

It can be stated that, compared to the reference scenario, the quantities of solid waste can be significantly reduced -by 48%-. Due to this fact, a reduction of the use of critical raw material flows is achieved. Most of the remaining solid waste is recyclable, which increases the industry circularity. Technical feasibility is a challenge to address, as more storage space at the production site and suitable recycling or partner installations are needed.

From the cost perspective, we estimate a TCO reduction potential per PV module of 2.59% from the reference case by applying the Vertical Integration and Revalorised Waste strategies. Additionally, we identified that raw materials cost are responsible for almost 70% of the TCO per PV module, this means that a systematic control of material flows, and waste minimization strategies should be seen as essential for manufacturing companies in this sector.

From the environmental perspective, we estimate a possible reduction of the environmental impacts of PV module production of at least 0.6 to 2.3% -depending on the impact category- compared to the defined reference case by combining both investigated circularity strategies.

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6 AUTHOR CONTRIBUTION STATEMENT

P. Brailovsky: Conceptualization, Material flows and total cost of ownership modelling, Laboratory work, Data curation, MFA and TCO Investigation, Methodology and Validation, Writing - Original Draft, Review & Editing; K. Baumann: Conceptualization, extended waste register, Waste management Investigation and Methodology, Writing - Original Draft, Review & Editing; M. Held: Conceptualization, LCA Investigation and Methodology, Writing - Original Draft, Review & Editing; A.-K. Briem: Conceptualization, LCA Investigation and Methodology, Writing - Original Draft, Review & Editing; K. Wambach: Conceptualization, Waste management Investigation and Methodology, Writing - Original Draft, Review & Editing; E. Gervais: Conceptualization, Investigation, Methodology, Writing - Original Draft, Review & Editing; S. Herceg: Conceptualization, LCA Investigation and Methodology, Writing - Original Draft, Review & Editing; B. Mertvoy: Waste management Investigation and Methodology - Original Draft; S. Nold: Review & Editing, J. Rentsch: Supervision & Funding acquisition

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