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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 5GWp PV module production cluster. Environmental impact reductions of 0.6–2.3% are estimated for different impact categories. We also estimate a cost reduction potential of 2.59% from total module costs.

Keywords: Photovoltaics / revalorized wastecircular 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.

PV end-of-life recycling, repair options and circular business models have gained significant attention over the last years [4–6], thus paving the way for the responsible management of modules once they reach their end-of-life. 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 identification and assessment of sound technological concepts with potential improvements to energy and resource use efficiencies along the PV production chain are of very high relevance for the future development of the industry [7]. The development of a detailed MFA bottom-up model for the main processes, the facilities and waste treatment requirements that support the production process is innovative, as it allows a holistic understanding of current resource needs and the identification of environmental and economic hot spots. The generation

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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 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. The metallurgical grade silicon (MG-Si) is to be produced in the Yunnan province, the poly-Si and Cz (Czochralski) ingots in Inner Mongolia and the wafers, solar cells and modules in Jiangsu province, representing current typical PV manufacturing regions for each.

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 with detailed bath/chamber modelling of in- and output flows. Considers process yields, scrap generation, tool availability, cycle times, batch sizes (for batch processes) and tool area footprint.
- Level 2: Production line and supply infrastructure. Includes exhaust, scrubbers, cooling towers, process water chillers, compressed dry air supply, deionized water supply and line automation.
- Level 3: Total factory including integrated building energy modelling. Includes room conditioning, ventilation, lighting, auxiliary equipment and services.

The MFA and TCO are calculated with Fraunhofer's ISE technology and cost assessment model Scost [8] which follows mainly the standards SEMI E35 [9] and E10 [10] 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.

Table 1. Products specifications per factory.

Wafers		
Crystallization type		Cz
Base Doping		p-Type
Thickness	μm	170
Wafer Edge Length	mm	156.75
Wafer Shape		Pseudo Square
Diameter if Pseudo Square	mm	210
Wafer Area	cm^2	244.32
Volume	cm^3	4.15
Density	g/cm^3	2.34
Wafer Mass	g	9.70
Cells		
Ø Cell Power (Pmpp)	5.37	Wp
Ø Cell Efficiency	22%	%
Cell Mass	g	9.19
Modules		
Cell per Module	60	Cells
Ø Module Power (Pmpp)	316.80	Wp
Ø Module Efficiency	19.9%	%
Module length	mm	1,633.90
Module width	mm	977.90
Module Area	m^2	1.598
Module Mass	kg	18.72

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 [11] and 14044 [12] standards. The LCA is based on the described MFA model and implemented using the GaBi software and its databases (version CUP 2022_1) [13]. The Life Cycle Impact Assessment (LCIA) is based on the suggested impact method set of the EU Environmental Footprint, Version 3.0 (EF3.0) [14].

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 1. The system boundary is *cradle-to-gate,* considering the impacts along the entire value chain until the PV module factory gate as shown in Figure 1.

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.

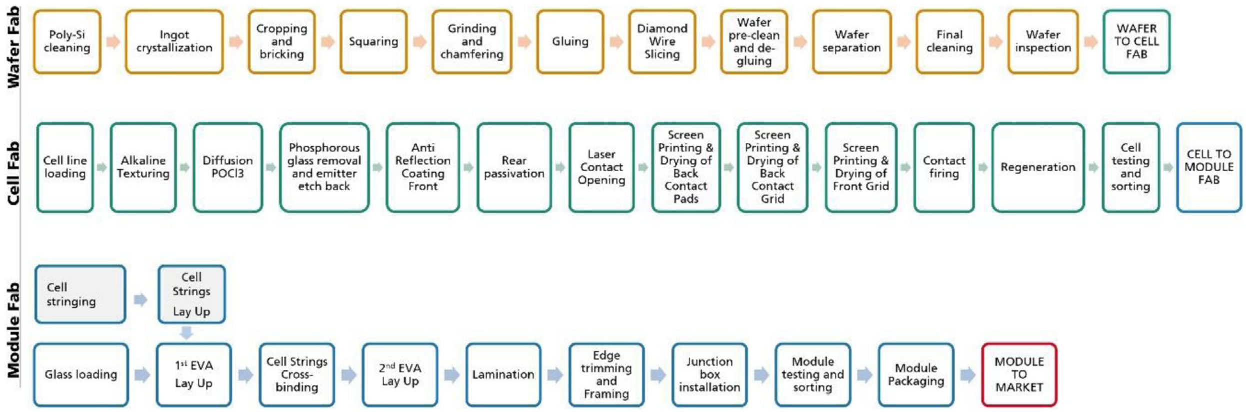

Fig. 1. Reference production chain scenario, from polysilicon to PV modules.

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 1.

In Figure 1 all the assessed processes from polysilicon to PV modules are shown. The wafer fab includes the Cz ingot crystallization step, the cutting processes from ingot to wafers and their cleaning. The cell fab starts by removing the saw damages on the wafers and texturizing them, the n/p junction is then formed by emitter doping, then the cells are passivated, metallized and tested. On the module fab the PERC cells are interconnected and laminated within glass, encapsulant (ethylene vinyl acetate −EVA-) and backsheet, before being framed, wired, tested and packaged.

2.1.1 Ingot and wafer FAB

In Figure 2 the material flow diagram of the ingot and wafer fab is presented via a Sankey diagram. The main flow represents the 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 68% of the virgin polysilicon feed is transformed into wafers, the rest 32% ends up as pot scrap, dust or silicon kerf loss on the industrial wastewater, with press filtration it is possible to recover 3890 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 recovery potential of silicon pot scrap and wasted crucibles sum up 1737 Mg per year. See Appendix A for further details.

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 5GWp 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

In Figure 3 the material flow along the module factory is presented for the production of one square meter of PV modules. The raw materials shown at the left side of the diagram are supplied to the respective processes on the middle of the diagram and the outputs from the factory are

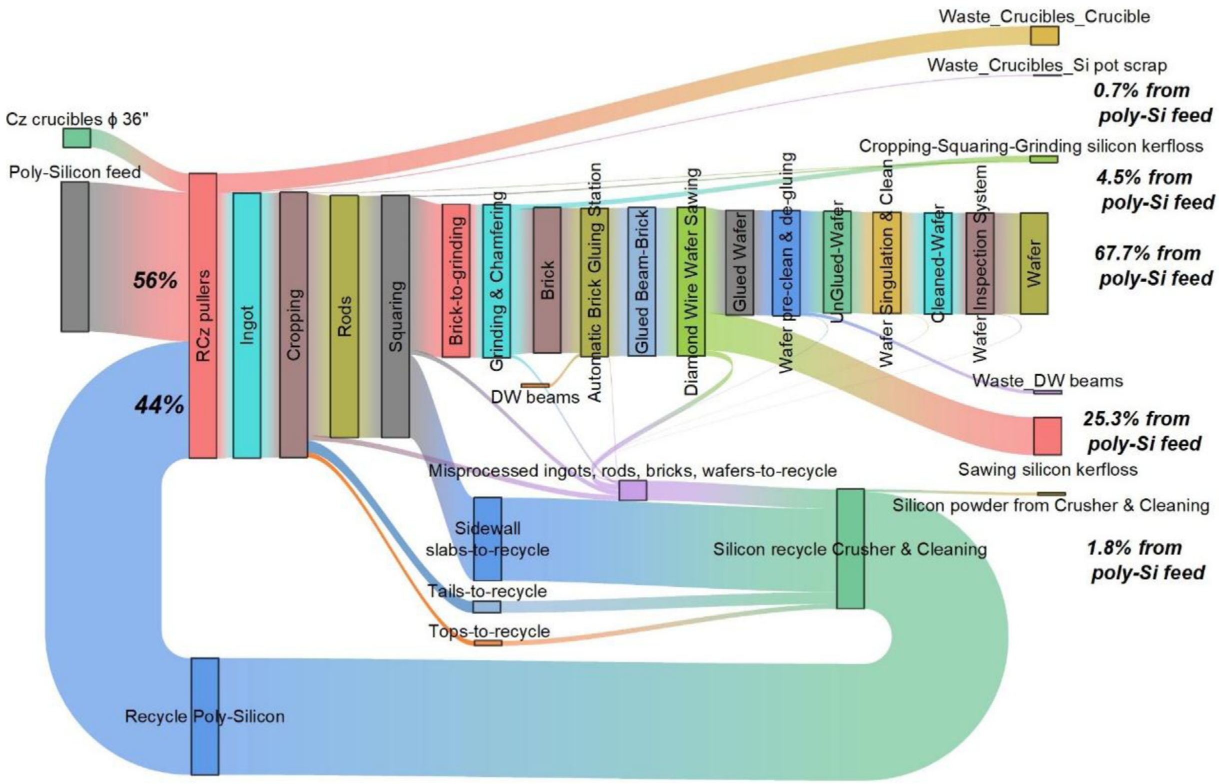

Fig. 2. Ingot and Wafer fab — Material flow diagram (reference) [Mg/year].

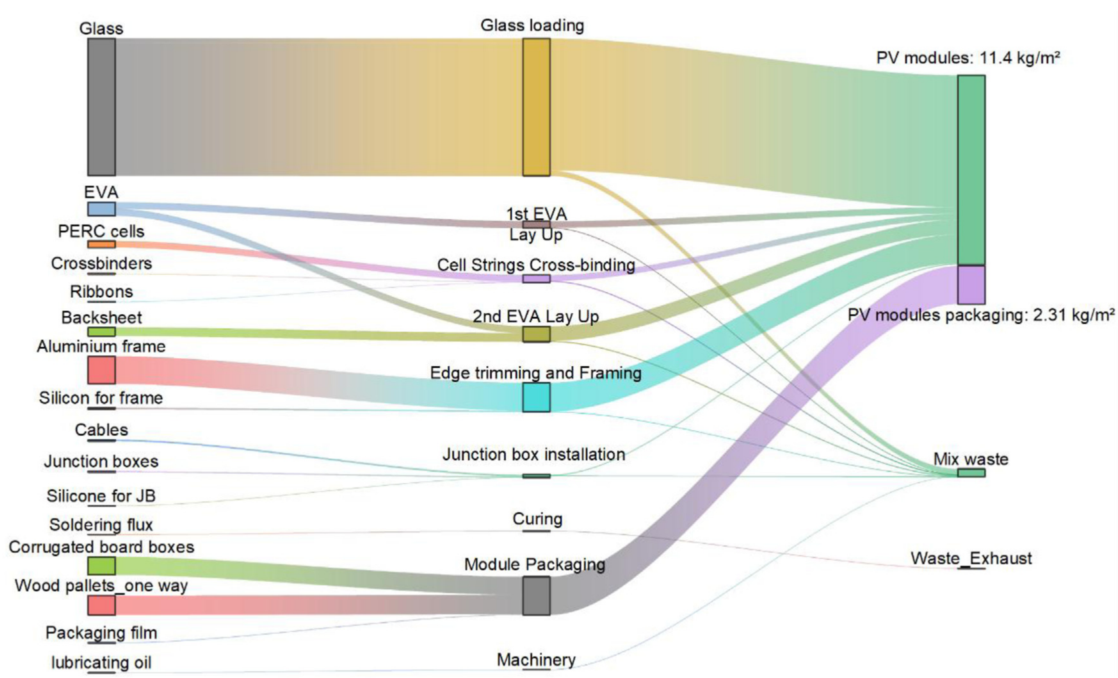

Fig. 3. Module factory — Material flow diagram (reference) [kg/m^2].

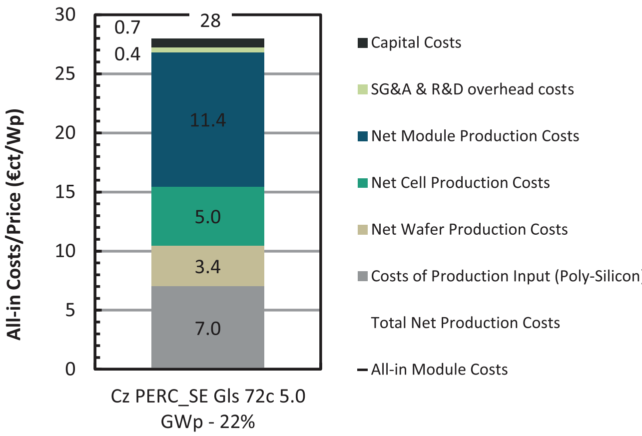

Fig. 4. PV module cost per component (reference).

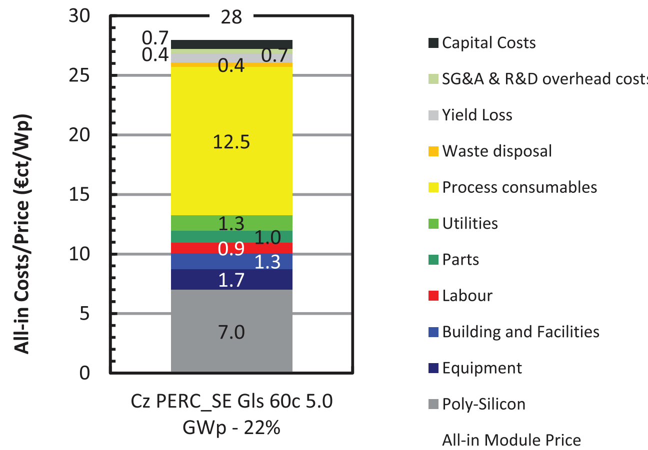

Fig. 5. PV module cost per cost categories (reference).

shown on the right side. 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, see Appendix B for further details. In terms of the annual 5GWp module production capacity –eq. to 25.500.741 m^2 of PV modules– the generated mix waste in the module factory sums up 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 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 [15]. Our cost estimation seems plausible as we calculate our reference for the older wafer format M2.

In Figures 4 and 5 we present the TCO distribution per component and per cost categories, respectively. 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 with the price assumption of 28.2 €/kg—and that the PERC cells have a cost of ownership that represents over 55% of the TCO of a PV module, 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. In Appendix C the considered costs for solid waste can be found, these include transportation cost. 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.

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 [16], Waste Framework Directive [17] and the CLP Regulation [18], which must be transposed into national law by the member states. These are authoritative for local operations.

According to [19] 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

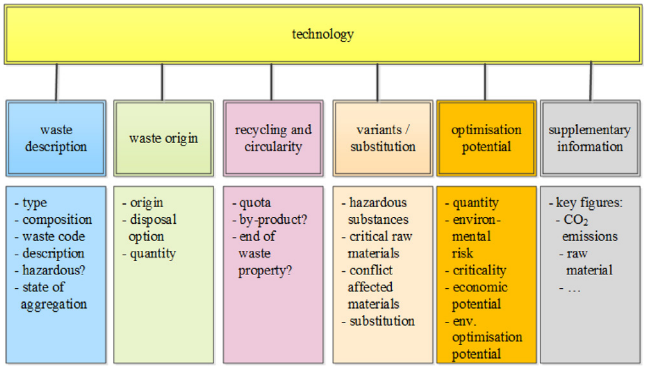

Fig. 6. Structure created extended waste register.

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 exist [19].

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. Figure 6 shows the schematic structure of the created database with all headings.

Identified wastes were grouped into waste categories (paper, metals, glass, etc.). Subsequently, the wastes were described by composition (heading: waste description) and extended by information on the waste-generating link within the production chain (heading: 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 (heading: variants and substitution). The consideration of the optimization potential includes the aspects that are relevant for the hot spot identification (heading: optimization potential). Beyond these aspects, the database can be extended, for example, by plant-specific key figures (heading: supplementary information).

The current waste register contains only the main waste fractions e.g. packaging waste, Si waste, etc. More waste fractions originate e.g. from waste generated during maintenance and can differ between plants in quality and quantity.

Recycling options differ depending on the location of the fabrication. Country-specific legislation and available collection and processing structures form the possible framework.

According to [19], 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 [19], 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 [20]. For specific wastes, in particular wastes containing silicon, the distribution was estimated based on the experience of the project participants.

These quotas are the result of published statistics, material flow diagrams, etc. and represent a wide range of options. For individual companies, however, there may be significant differences, depending on the technical possibilities and the legal and economic framework conditions that apply locally.

2.2.3 Differentiation of hazardous and non-hazardous waste

The classification of waste as hazardous or non-hazardous is a serious decision in the entire chain of waste management from origin to final treatment. Depending on the classification, legal consequences as well as treatment and transportation in compliance with regulations are to be expected. Furthermore, additional costs may incur.

The assessment of waste streams is influenced by local legal requirements and by the knowledge of the composition or processing of the substances, which ends up in the waste fractions. The present assessment refers to the waste streams generated during manufacturing. Material Safety Data Sheets, results of analytical reports and information provided by the project partners were used to assess the composition and substances used in the waste generating process. The waste assessment is based on information about the content of substances and their (possible) combination in the waste streams (solid, liquid, gas) at least for antimony, arsenic, lead, cadmium, chromium, cobalt, copper, nickel, mercury, selenium, thallium, organic tin, zinc, beryllium, silver, vanadium, barium, molybdenum, phenol, cyanide. Information on the hazardousness of the potential substances and potential hazardous compounds were gained either from project partners or entries in publicly available databases.

As legal basis the European waste and chemical legal framework was used. The European framework bases on international agreements and the Chinese waste management organisation is oriented on the European one [19]. Thus, it was assumed, that the differences are minor.

3 Potential improvements in terms of circularity

From the established reference processes, a set of potential resource saving actions were derived. These are described and their benefits quantified and shown below.

3.1 Vertical integration

We use the term vertical integration for stating that the manufacturing of multiple products in the production chain takes place at the same industrial site. This is a company strategy to establish its own supply instead of outsourcing it. Vertical integration from polysilicon to PV modules allows the direct transportation of wafer and cells staples from the wafer to cells and from the cells to modules factories, respectively. In the cell factory the undoped wafers scrap can be collected and transported to the polysilicon cleaning wet chemistry baths for reuse on the polysilicon feed for ingot crystallization. Electrical substation, chemicals storage tanks, wastewater treatment, clean dry air generators, ventilation and exhaust systems, cooling towers, water chillers, fire protection system, solid waste handling and storage, reliability and maintenance machinery and workshops, physical security, communications network, administrative and logistic facilities can be shared for all factories.

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.

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.

Some potential improvements associated with the vertical integration of manufacturing operations are shown below:

– Effects on polysilicon consumption. Integrating ingot, wafer and PV cell fabs enables an increase in polysilicon utilization. First, avoiding packaging, storage, transportation and packaging removal steps for wafers and cells reduce scrap losses. Second, if contamination with other waste sources is avoided, wafers scrap and work in process cells before doping can be crushed and chemically etched to reclaim the polysilicon to produce new ingots.
– Effects on plastic, paperboard and wood waste. Avoiding wafer and cell packaging, storage, transportation and packaging removal steps is possible to reduce wafer and cell scrap and the packaging materials. By doing this the waste generation is also reduced. In Figure 7 typical wafer and cell packaging materials are shown, for our estimations we weighted at Fraunhofer ISE's laboratories samples of the packaging.
– Other positive effects. The planning of utilities and facilities to supply electricity, de-ionised (DI) water, process cooling water (PCW), clean dry air (CDA), feedstock material, gases and chemicals can be optimized to save space and resources at the production site. We have identified very important water and waste heat recovery and reuse opportunities that we plan to address in further publications.

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 2205 Mg per year. The demand for raw silicon is reduced by 75 Mg per year for the 5 GWp PV module cluster.

Fig. 7. Top: 40,000 wafers packaged over a wood pallet. Bottom: Expanded polystyrene box containing 200 M2 wafers.

From the cost perspective, our results show that the Vertical Integration of the factories enables a total cost reduction per module of almost 1%. Around 53% of this reduction is explained by the avoidance of wafer and cell packaging costs, 28% due to the reduced waste and cell scrap and 15% due to the reduced virgin polysilicon requirement due to the reclaim of wafer scrap from the cell fab processes before phosphor diffusion.

3.2 Revalorized waste

To evaluate the potential improvements in terms of circularity, the scenario "revalorized waste", visualized in Figure 8, and criteria to compare advantages and disadvantages of the improvement scenario to the reference scenario were developed.

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

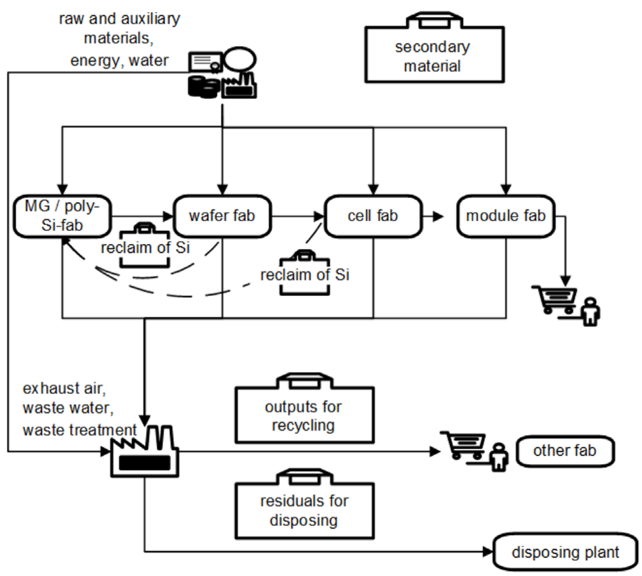

Fig. 8. Revalorized waste for more recycling and circular production.

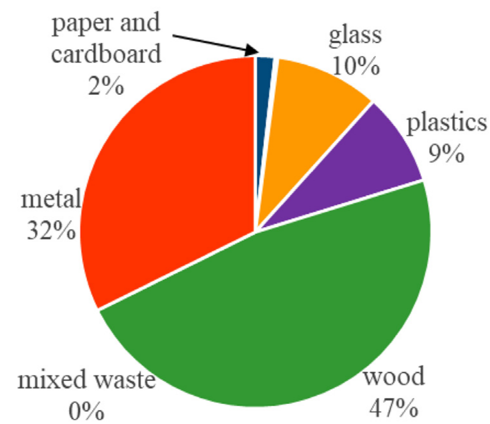

Fig. 9. Poly-Si to PV modules waste flows.

on location of the plant. By experiences of own projects and interviews and desk research (e.g. [20–32]) the authors identified various possibilities for revalorizing the outputs. For example, Si-scrap like tops, tails, sidewall slabs or broken wafers can be reused for the production of Si ingots. The Si-kerf can be used to produce silicon nitride (Si_4N_3) crucibles or SiC. A use in metallurgy for battery electrodes or in the production of hydrogen is also possible. Quartz can be used as an SiO_2 substitute in Si production, for cristobalite production or as a filling material for gabions, in the production of terrazzo-like tiles, as well as a decorative material. Recycling in the ceramic industry is also possible. A recovery of solar cells requires a complete separation of the individual layer metallization layers. Only cells that are still functional can be cut into smaller pieces and used in solar-powered devices and gadgets. 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. Chemical recycling methods are currently being investigated. Currently, the polymers can be used, e.g. as substitute fuel for energy generation or as a synthesis gas. The glass is mainly used for the production of glass fibers or foam glass. For clean glass without adhesives, recycling in the flat glass or container glass industry is also possible in principle. Ideally, intact glass panes can be reused to produce PV modules, although frequent product changes with altered sizes and surface damage (corrosion, erosion, scratches, etc.) mean that this route can only be used to a limited extent.

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. Copper with coatings of tin and lead can be recycled in copper smelters. Silver from the solar cell can be separated and recovered by etching or melting down. Cables can be recycled by cable recyclers. Waste paper 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.

Recycling options vary depending on the location of the manufacturing facility. Country-specific legislation and available collection and processing structures provide the possible framework.

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 estimation was based on European recycling quota and own experiences made in projects, interviews and desk research (e.g. [20–32]).

The occurring waste flows, including packaging and residues, were classified by type and can be seen in Figure 9 .

The value of the wastes is assessed to suggest their treatment in terms of material recycling, energetic recovery and waste disposal as shown in Figure 10.

Additionally, it is stated, that a reusable wood pallet system is adopted between each fabrication site. Using reusable pallets instead of single-use pallets can avoid much packaging waste as shown in Figure 11.

Total cost reduction per module of 1.65%, 69% of this amount 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 (for the steel industry) or in the aluminium and MG-Si manufacturing, 5% for the aluminium recycling and 3.5% for the metallized cell scrap.

The amount of waste to be disposed of could be reduced by approx. 43% compared to the reference scenario, which represents 9112 Mg per year. By using a corresponding plant for recycling and energy recovery using of reusable pallets instead of disposable pallets, 35% of the generated reference waste could be considered as recycled, 9% as

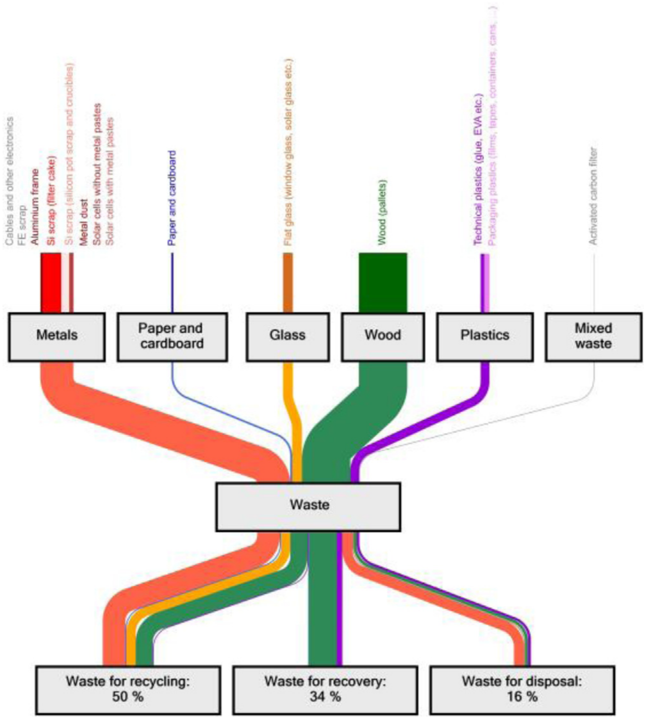

Fig. 10. Poly-Si to PV modules waste flows with recycling options.

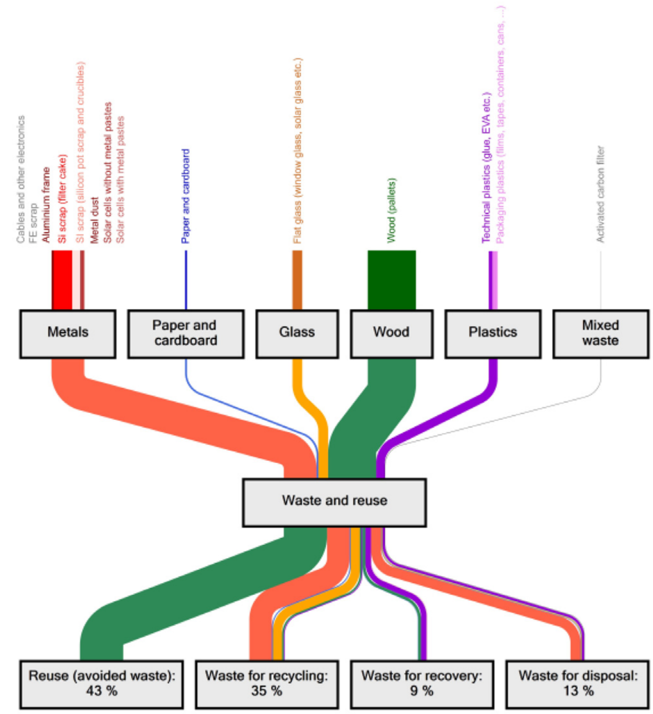

Fig. 11. Poly-Si to PV modules waste flows with recycling options using reusable pallets.

energy recovered. The rest would have to be disposed of in a landfill. See Appendix D for complete waste cataster of all scenarios.

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 (see Tab. 2). 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 (as defined in Tab. 2). 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 to avoid an over- or under estimation of the potential benefits. An alternative *avoided burden approach* could quantify further environmental benefits and is discussed in Section 4.

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

First, the reduction potentials regarding the waste treatment scenarios are evaluated using the example of the carbon footprint, i.e. EF3.0 Climate Change indicator. In the next step, the LCIA results of investigated waste reduction scenarios are put into context of the entire PV module production for several impact categories to identify the environmental reduction potential on a product level.

3.3.2.1 A closer look on EF3.0 climate change

The results of the reference case (all wastes to disposal) for EF3.0 Climate Change show a high contribution of wastes of the wooden one-way pallets put to landfill in the

Table 2. LCA model assumptions for waste treatment paths.

Waste stream	Assumptions for waste treatment options in LCA model		
	Recycling	Thermal recovery	Disposal
Paper and Cardboard	Paper and cardboard recycling	Waste incineration and disposal	Waste incineration and disposal
Mixed Wastes	N/A	N/A	Waste incineration and disposal
Glass	Glass cullet downcycling for other application, e.g. foam glass production	N/A	Inert waste on landfill
Plastics (packaging, technical plastics)	Packaging plastics: shredding and granulation incl. losses; no recycling of technical plastics	Plastics in waste incineration	Plastic wastes on landfill
Wood (pallets)	Pallet recycling	Wood waste in waste incineration plant	Wood waste on landfill
Metals			
Ferrous metals	Steel recycling incl. secondary material production and recycling losses	Waste incineration (no energy recovery)	Steel waste on landfill (inert matter)
Aluminium	Aluminium recycling incl. secondary material production and losses.	Waste incineration (no energy recovery)	Aluminium waste on landfill (inert matter)
Cables	Copper recycling incl. secondary material production and losses; Plastic insulation: Waste incineration.	N/A	Waste on landfill (plastic wastes and inert matter)
Silicon and solar cells	Recycling as substitution material of metallurgical grade silicon in lower application (e.g, aluminium industry ore silicone)	N/A	Waste on landfill, inert wastes
Metal dust (filters)	N/A	N/A	Waste on landfill, inert wastes

reference scenario which account for approximately 95% of climate change impacts. These contributions are mainly related to the released methane emissions caused during the rotting processes. The contributions of the disposal of other wastes to climate change are comparably low in this scenario and in the case of glass and metal wastes mainly caused by the operation of the landfill site.

In comparison to the reference scenario, the results of the vertical integration scenario show a reduction potential of around 13% for EF3.0 Climate Change. These are mainly achieved by the reduction of required one way-pallets and packaging materials (paper/cardboard and plastic) due to avoided transports between the single production process steps in the upstream processes of solar cells and module assembly.

The revalorized waste scenario (cut-off approach) shows a high reduction potential and especially in combination with the vertical integration scenario, which lead to reductions of climate change results from 80% to 85%.

3.3.2.2 Circularity strategies reduction potentials

Figure 12 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).

In contrast to the LCA results on the waste treatment level, the following evaluation also takes into account the reduced environmental impacts from avoided material production, due to the reduced use of packaging materials and transport wastes in the production.

This means that for the scenario of the vertically integrated production, reductions compared to the reference scenario also reflect savings related to the avoided production of packaging materials, such as paper and plastics as well as slightly reduced losses to wafer breakage during transportation. Reductions on the production side of the revalorized waste scenario relate to the change from one-way pallets to reusable wood pallets.

As Figure 12 shows, the environmental effect of avoided use of packaging materials in a vertically integrated

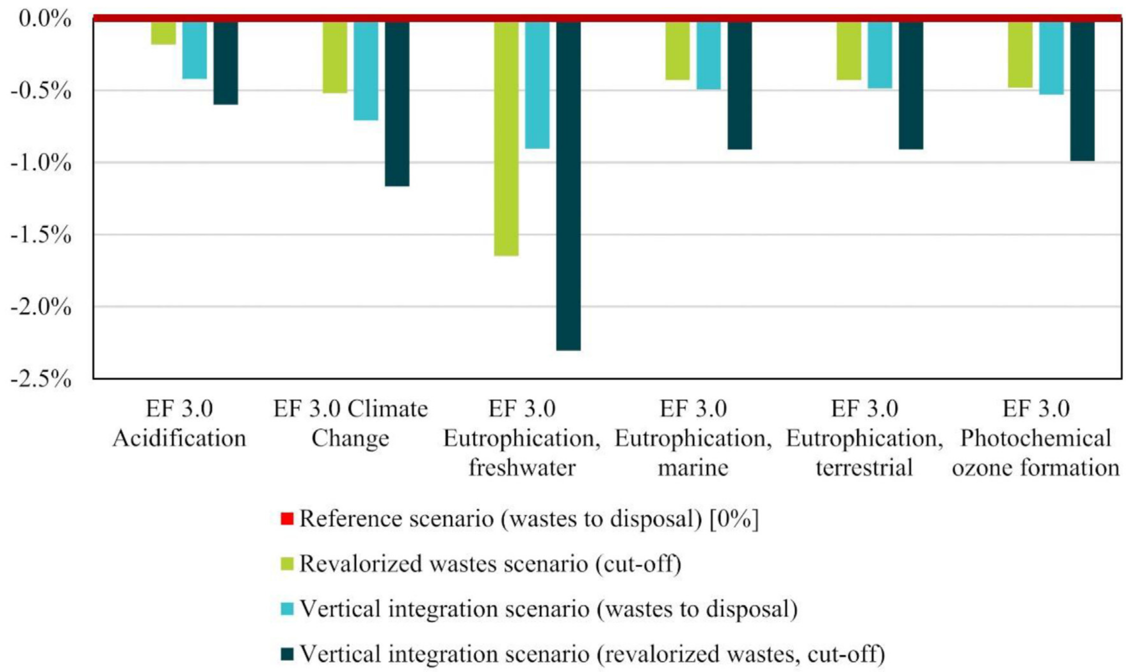

Fig. 12. Environmental impact reduction potentials of investigated solid waste reduction and treatment strategies in relation to the reference PV module production (module level).

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 only 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 supplementary, the highest savings of environmental impacts are reached with this scenario in all investigated impact categories.

4 Summary and discussion

4.1 Results comparison

The implementation of both the Vertical Integration and Revalorised waste strategies translates into a total cost reduction per PV module of 2.59% from the reference scenario, a cost 54.01 € per square meter of PV module is achieved. Around 42% of the reduction is explained by the establishment of a reusable pallet system, 21% due to the avoided wafer and cell packaging costs, 11% due to the reduced waste and cell scrap, 11% for the silicon waste recycling as ferrosilicon for the steel, aluminium and MG-Si manufacturing, 6% due to the reduced virgin polysilicon requirement due to the reclaim of wafer scrap from the cell fab processes before diffusion, 3% for the aluminium scrap recycling and 2% for the metallized cell scrap.

The overall amount of waste to be disposed of could be reduced by approx. 48% compared to the reference scenario, which represents 10,145 Mg per year. As shown in Figure 13.

If corresponding plants for recycling and energy recovery are available and used and reusable pallets instead of disposable pallets are used, 33% of the generated reference waste could be considered as recycled, 7% as energy recovered The other waste would have to be disposed of in a landfill.

The LCA analysis revealed the environmental benefits of the proposed strategies. The savings of intermediate packaging materials between process steps from ingot to cell production as presented for the vertical production scenario is seen as a promising approach as it reduced environmental impact of the production and disposal of required packaging materials, as well as reduced impacts from breakages during transports. Furthermore, the revalorized wastes scenario shows a high potential of reducing environmental impacts from production waste treatment when enabling appropriate waste separation on the production site. By combining both strategies the environmental impacts of PV module production can be reduced by 0.6–2.3% compared to the defined reference case and depending on the impact category. Our first estimates on potential additional benefits from material recycling and energy recovery, especially in case of the large mass streams of silicon waste, shows that savings can be significantly increased when considering avoided burdens. Another aspect that has not been taken into account in this analysis but could lead to further reductions are avoided transport processes in the vertical

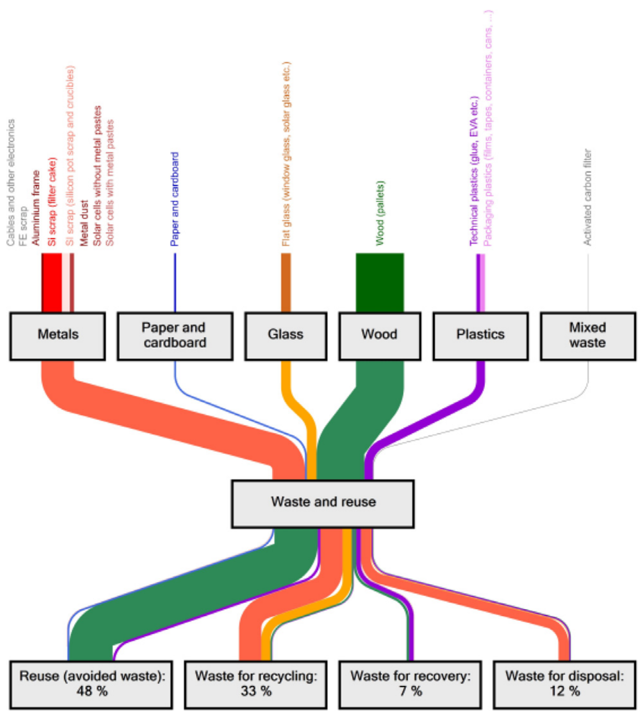

Fig. 13. Poly-Si to PV modules waste flows with recycling options in combined scenario.

integration scenario. However, for the revalorised waste strategy a potential higher effort for logistics could have an opposing effect.

In general, the economic and environmental benefits are achieved by integrating all transforming activities at one site, avoiding intermediate products packaging, revalorising waste streams, and implementing a reusable wood pallet system within the PV cluster, with suppliers and with the PV modules market.

4.2 Impact on global silicon supply

Besides their economic and environmental benefits, the Vertical Integration and Revalorized waste strategies can contribute to reducing material supply risks, at the company level as well as on a global scale.

PV manufacturing being a mature, largely optimized industry, a reduction of 75 Mg of virgin polysilicon per year and per 5 GWp PV module output (i.e., 0.5% reduction) via vertical integration admittedly does not compare to the reduction potential of technological changes. For instance, reductions of 25–30% for the poly-Si consumption for mono-Si wafers can be expected by improving crystallization and wafering yields and especially by reducing wafer thickness and kerf loss [33]. Nevertheless, at a company level, vertical integration can be a strategy for PV manufacturers to limit their supply dependencies. As a result, supply bottlenecks can be mitigated to a certain degree, and a greater control is obtained over the supply chain in terms of costs and material origins – which might become increasingly relevant in the context of due diligence and taxonomy regulations. Maintaining flexibility and high innovation grade might be a challenge in a vertical integration but is crucial as PV technologies evolve rapidly.

In the context of a PV annual terawatt growth which is expected before 2030 [33], material savings from the investigated strategies also contribute to a more sustainable raw material production. Vertical integration can avoid the consumption of around 15,000 Mg virgin poly-Si/TWp. This represents 2.6% of the global poly-Si production in 2021 [34]. Revalorized waste strategies lead to the recycling of around 800,000 Mg poly-Si/TWp, feeding the ferrosilicon industry. This represents about 10% of the global ferrosilicon production in 2020 [35].

4.3 Critical aspects for implementation of potential optimizations

The scenarios have shown a big potential to reduce the waste and/or to revalorize the solid waste. Some critical aspects, must be considered for the implementation in a real plant which can lead to a rebound effect:

- The recycling of mixed input waste fractions to a well specified output of sufficient quality and purity for direct use in the value chain is a complex task. For example, the additives present in the plastics can reduce the potential for closing the loop directly. Solvent or chemical recycling methods are currently available for some types of packaging plastics, but even in these cases remaining additives and impurities can hinder the recycling in sufficient quality and yield. Solvent or chemical recycling methods for backsheet foils and other plastic used in the modules have still to be developed.
- Cutting fluids and other processing aids used in the production chain can reduce the recycling options of Si-kerf loss and scrap by failing to fulfill the quality demands of an economic melting process so only downcycling remains.
- To realize a consequent separate collection of waste in their different fractions, more storage place is needed, the employees must do the surplus work and additional costs could make the process less profitable.
- Finally, specific treatment plants and markets for secondary material must be available locally to minimize transport.

The Vertical Integration of an industrial clusters offers many advantages but finding a location to accommodate a 5 GWp per year PV module cluster is a challenge itself. A site with approximately 30 hectares is needed and the location should have redundant and stable interconnections to power lines, access to sufficient water resources, availability of skilled technicians and operators and, especially for the module factory, excellent logistic interconnections to supply raw materials and to deliver PV modules to the targeted markets.

4.4 LCA limitations and challenges

Based on the presented modelling approach, our LCA analysis allows a first estimate of the environmental reduction potentials of the proposed strategies. However, due to the limited availability of specific inventory data regarding the disposal or further treatment options of PV specific materials, these results arise with uncertainties. Variations on LCA results due to LCA databases and software are also a documented challenge [36]. Hence, there is a need for further research on the specific emission profiles of waste specific treatments in the PV industry. Furthermore, the full processing of silicon waste from PV productions for the use in other application need to be analysed in more detail by representing data from real use cases, e.g. to be used as a substitute for metallurgical grade silicon in the aluminium industry.

5 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. Especially emphasis should be taken for polysilicon, solar glass, aluminium frames, encapsulant and backsheet foils, metallic pastes, crucibles and pullers hot zones.

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. Further reduction potentials could be unlocked by considering avoided burdens, especially from silicon waste.

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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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Appendix A: Material flows from polysilicon to as-cut wafers

Input Node/Link	Output Node/Link	Units
		Mg/year
Poly-Silicon feed	RCz pullers	14593,3
Recycle Poly-Silicon	RCz pullers	11413,3
Cz crucibles ϕ 36"	RCz pullers	1830,9
RCz pullers	Waste_Crucibles_Si pot scrap	104,0
RCz pullers	Waste_Crucibles_Crucible	1830,9
RCz pullers	Ingot	25902,6
Ingot	Cropping	25902,6
Cropping	Rods	23672,7
Cropping	Tops-to-recycle	487,4
Cropping	Tails-to-recycle	1157,6
Cropping	Cropping-Squaring-Grinding silicon kerfloss	66,9
Rods	Squaring	23672,7
Squaring	Brick-to-grinding	14953,7
Squaring	Sidewall slabs-to-recycle	8120,0
Squaring	Cropping-Squaring-Grinding silicon kerfloss	125,6
Tops-to-recycle	Silicon recycle Crusher & Cleaning	487,4
Tails-to-recycle	Silicon recycle Crusher & Cleaning	1157,6
Sidewall slabs-to-recycle	Silicon recycle Crusher & Cleaning	8120,0
Misprocessed ingots, rods, bricks, wafers-to-recycle	Silicon recycle Crusher & Cleaning	1917,9
Silicon recycle Crusher & Cleaning	Recycle Poly-Silicon	11413,3
Silicon recycle Crusher & Cleaning	Silicon powder from Crusher & Cleaning	269,6
Brick-to-grinding	Grinding & Chamfering	14953,7
Grinding & Chamfering	Brick	14184,2
Grinding & Chamfering	Cropping-Squaring-Grinding silicon kerfloss	470,4
Brick	Automatic Brick Gluing Station	14184,2
DW beams	Automatic Brick Gluing Station	327,7
Automatic Brick Gluing Station	Glued Beam-Brick	14482,8
Glued Beam-Brick	Diamond Wire Wafer Sawing	14482,8
Diamond Wire Wafer Sawing	Glued Wafer	10250,5
Diamond Wire Wafer Sawing	Sawing silicon kerfloss	3692,8
Glued Wafer	Wafer pre-clean & de-gluing	10250,5
Wafer pre-clean & de-gluing	UnGlued-Wafer	9917,1
Wafer pre-clean & de-gluing	Waste_DW beams	327,7
UnGlued-Wafer	Wafer Singulation & Clean	9917,1
Wafer Singulation & Clean	Cleaned-Wafer	9897,2
Cleaned-Wafer	Wafer Inspection System	9897,2
Wafer Inspection System	Wafer	9877,4
Cropping	Misprocessed ingots, rods, bricks, wafers-to-recycle	518,1
Squaring	Misprocessed ingots, rods, bricks, wafers-to-recycle	473,5
Grinding & Chamfering	Misprocessed ingots, rods, bricks, wafers-to-recycle	299,1
Automatic Brick Gluing Station	Misprocessed ingots, rods, bricks, wafers-to-recycle	28,4
Diamond Wire Wafer Sawing	Misprocessed ingots, rods, bricks, wafers-to-recycle	539,5
Wafer pre-clean & de-gluing	Misprocessed ingots, rods, bricks, wafers-to-recycle	19,9
Wafer Singulation & Clean	Misprocessed ingots, rods, bricks, wafers-to-recycle	19,8
Wafer Inspection System	Misprocessed ingots, rods, bricks, wafers-to-recycle	19,8

Appendix B: Material flows from module fab

Input Node/Link	Output Node/Link	Units
		kg/m²
Curing	Waste_Exhaust	0.0174
Machinery	Mix waste	0.0016
Glass loading	Mix waste	0.0806
Edge trimming and Framing	Mix waste	0.0168
Cell Strings Cross-binding	Mix waste	0.0017
Lay Up	Mix waste	0.0080
Cell Strings Cross-binding	Mix waste	0.0101
Cell Strings Cross-binding	Mix waste	0.0072
PERC cells	Cell Strings Cross-binding	0.0238
EVA	1st EVA Lay Up	0.0154
EVA	2nd EVA Lay Up	0.0154
Backsheet	2nd EVA Lay Up	0.0197
Cell Strings Cross-binding	Mix waste	0.0238
Lay Up	Mix waste	0.0154
2nd EVA Lay Up	Mix waste	0.0154
2nd EVA Lay Up	Mix waste	0.0197
PERC cells	Cell Strings Cross-binding	0.3760
Glass	Glass loading	8.0574
EVA	1st EVA Lay Up	0.3992
EVA	2nd EVA Lay Up	0.3992
Backsheet	2nd EVA Lay Up	0.5106
Aluminium frame	Edge trimming and Framing	1.6772
Cables	Junction box installation	0.0990
Junction box installation	Mix waste	0.0014
Crossbinders	Cell Strings Cross-binding	0.0362
Ribbons	Cell Strings Cross-binding	0.0333
Silicon for frame	Edge trimming and Framing	0.0883
Silicone for JB	Junction box installation	0.0027
Soldering flux	Curing	0.0174
Junction box installation	Mix waste	0.0001
lubricating oil	Machinery	0.0016
Wood pallets_one way	Module Packaging	1.1735
Packaging film	Module Packaging	0.0358
Glass loading	PV modules	7.9769
Lay Up	PV modules	0.3912
Cell Strings Cross-binding	PV modules	0.3696
2nd EVA Lay Up	PV modules	0.8916
Edge trimming and Framing	PV modules	1.7469
Junction box installation	PV modules	0.0684
Module Packaging	PV modules packaging	2.3093

Appendix C: Costs for waste categories

	Waste category	Cost (−sign for incomes)	Price unit
Waste strategy ***considered on Reference and Vertical Integrated production scenarios***	Waste_Mix waste	138.95 [37]	€/Mg
	Waste_Wood	175.95 [38]	€/Mg
	Waste_Paperboard	−134.68 [39]	€/Mg
	Waste_Aluminium	−2484.05 [40]	€/Mg
	Waste_Steel	−382.05 [41]	€/Mg
	Waste_Copper	−7284.05 [40]	€/Mg
	Waste_Glass	90.95 [42]	€/Mg
	Waste_plastics	−84.05 [39]	€/Mg
	Waste_Inorganic waste	120.95 [38]	€/Mg
	Waste_Hazardous	1015.95 [38]	€/Mg
	Waste_WaferCell_Scrap_ no metal paste	−354.05	€/Mg
	Waste_Cell_Scrap_with metal paste	−2227.51	€/Mg
	Waste_Si powder wet cake	−875.05 [43]	€/Mg
All waste categories have embedded the transportation cost for 40t trucks with 120 km round trips	Waste_transportation cost	0.08 [44]	€/Mg*km

Appendix D: Waste flows for all scenarios for a 5GWp polysilicon to PV modules industrial cluster

Waste types and groups	Units	0) Reference	1) Vertical Integrated production	2) Revalorized waste							1+2) Vertical Integrated with Revalorised waste production			
Paper and cardboard				Recycling share	Energy recovery share	Disposal share	Recycling quantity	Quantity for energy recovery	Disposal quantity	Total	Recycling quantity	Quantity for energy recovery	Disposal quantity	Total
Paper and cardboard	Mg	382,92	0,00	57%	19%	24%	218,26	72,75	91,90	382,92	0,00	0,00	0,00	0,00
SUM	Mg	382,92	0,00											
Mix waste														
activated carbon filter		53,06	53,06	0%	0%	100%	0,00	0,00	53,06	53,06	0,00	0,00	53,06	53,06
SUM	Mg	53,06	53,06											
Glass														
Flat glass (window glass, solar glass, ...)	Mg	2054,71	2054,71	94%	0%	6%	1931,43	0,00	123,28	2054,71	1931,43	0,00	123,28	2054,71
SUM	Mg	2054,71	2054,71											
Plastics														
Packaging plastics (films, tapes, containers, cans, ...	Mg	1077,36	541,28	15%	39%	46%	161,60	420,17	495,59	1077,36	81,19	211,10	248,99	541,28
technical plastics (adhesives, EVA, ...)	Mg	749,56	749,56	0%	100%	0%	0,00	749,56	0,00	749,56	0,00	749,56	0,00	749,56
SUM	Mg	1826,92	1290,84											
Wood														
Wood (pallets...)	Mg	10125,47	8889,61	35%	58%	6%	358,44	589,30	64,80	1012,55	336,14	552,63	60,77	949,53
SUM	Mg	10125,47	8889,61											
Metals														
Ferrous scrap	Mg	27,21	27,21	83%	7%	11%	22,58	1,90	2,99	27,21	22,58	1,90	2,99	27,21
Aluminium frames	Mg	427,69	427,69	75%	9%	16%	320,77	38,49	68,43	427,69	320,77	38,49	68,43	427,69
Cables and other electronics	Mg	43,01	43,01	70%	0%	30%	30,11	0,00	12,90	43,01	30,11	0,00	12,90	43,01
Si-Scrap (Filter cake)	Mg	3889,87	3869,80	100%	0%	0%	3889,87	0,00	0,00	3889,87	3869,80	0,00	0,00	3869,80
Si-Scrap (Silicon pot scrap und Crucibles)	Mg	1737,64	1728,67	0%	0%	100%	0,00	0,00	1737,64	1737,64	0,00	0,00	1728,67	1728,67
Metal dust	Mg	237,46	240,75	0%	0%	100%	0,00	0,00	237,46	237,46	0,00	0,00	240,75	240,75
Solar cells scrap with metal paste	Mg	348,88	347,25	90%	0%	10%	313,99	0,00	34,89	348,88	312,52	0,00	34,72	347,25
Solar cells scrap without metal paste	Mg	193,09	170,51	90%	0%	10%	173,78	0,00	19,31	193,09	153,45	0,00	17,05	170,51
SUM	Mg	6904,85	6854,88											
Total	**Mg**	**21347,93**	**19143,10**				**7420,84**	**1872,19**	**2942,25**	**12235,01**	**7057,99**	**1553,69**	**2591,63**	**11203,03**