ECO-SOLAR FACTORY: ENVIRONMENTAL IMPACT OPTIMISATION OF PV PRODUCTION

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ABSTRACT: This conference paper deals on one hand with the monitoring of the current degrees of achievement of the targets of the European H2020-FOF-13-2015 Eco-Solar project regarding project targets in material reduction. On the other hand the environmental impacts like carbon footprint, acidification or resource depletion of the current processing status of the individual work packages are considered in relation to the environmental impacts of the manufacturing processes of state of the art PV modules (baseline).

In the halftime assessment, by implementing all previous project developments into the production process chain (ingot → wafer → cell → module) the project target reduction demand of aluminium can be achieved totally for both, mono- and multi-Si based PV modules, the project target reduction demand of argon gas can be achieved totally for mono-Si based PV modules only. Most of the other project targets benefit as well, but without achieving the target values yet.

Compared to the results of state of the art PV modules (baseline) environmental advantages exist for almost all examined impact categories. The only exception is eutrophication terrestrial of the improved production process of multi-Si based PV modules. In the case of climate change, the greenhouse emissions are reduced by more than 11 % for mono-Si based PV modules and more than 15 % for multi-Si based PV modules. The improvements trace back to the ingot production as well as module production mainly and to a lower proportion to the wafer production.

Keywords: LCA, LCI, carbon footprint, material reduction, resource depletion, mono-Si based PV modules, multi-Si based PV modules, eco-efficiency analysis

1 AIM AND APPROACH USED

The European H2020-FOF-13-2015 Eco-Solar project that started in October 2015 envisions increasing resource and energy efficiency over the entire photovoltaic value chain, while simultaneously maximising recycling and remanufacturing efficiencies, by introducing design for recovery, repair and reuse, and collaborating for improvements in waste reduction. Reusing materials and reducing the consumption of raw materials will make solar cell panels both cheaper and greener.

One of the main aims of work package 5 “Environmental impact and repurposing of waste products” is to provide a comprehensive analysis of the progress made with respect to environmental impacts. First results from the initial assessment at start of the project (benchmark processes) and the midterm assessment are presented. The implementation of the new eco-friendly production methods requires an ecological validation and has to be economically viable as well. bifa therefore carried out an eco-efficiency analysis according to figure 1. The reference module is a standard module (glass-EVA-Tedlar laminate, nominal power of 270 Wp, 60 cells with an area of 156 x 156 mm each).

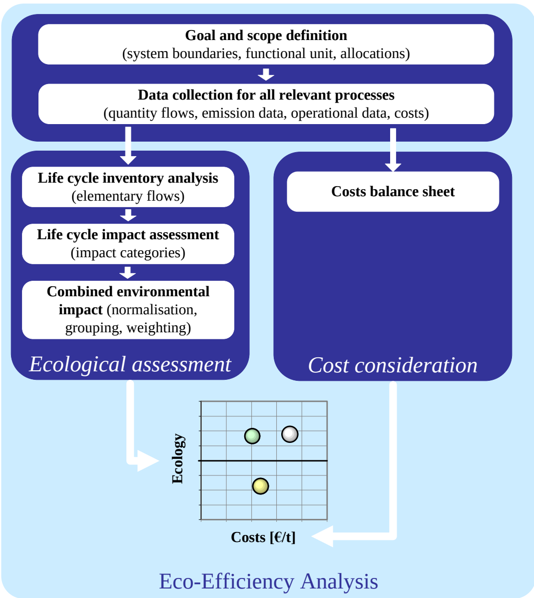

Figure 1: Eco-efficiency analysis carried out by bifa

2 SCIENTIFIC INNOVATION AND RELEVANCE

The input data collection for the initial LCI was based on a state of the art module design: standard EVA laminated module (60 6-inch solar cells, about 270Wp) with front glass and polymer back sheet including aluminium framing. All relevant production steps starting from the ingot casting were modelled using LCI data provided by all partners. Data gaps were filled by using preferably recently published data and expert assumptions. Preliminary baseline data of the PV-module production as well as data sets for standard processes like energy supply, transports etc. from professional data bases are used as basis in the material and energy flow modelling [1 - 5]. The model structure is designed to facilitate a sectoral evaluation of the results of the LCA (Life Cycle Assessment). The LCI (Life Cycle Inventory) baseline of the individual sectors of the PV-module production (ingots, wafer, cell and module) is finished.

This conference paper deals with first monitoring results of the current degrees of achievement of the project targets regarding material reduction. Most important reduction potentials of waste and resource consumption are shown in figure 2. The environmental impacts of the current processing status of the individual work packages are considered in relation to the environmental impacts of the manufacturing processes of state of the art PV modules, based in LCI baseline. For this, a midterm, preliminary LCA has been prepared on the basis of data from the project partners regarding the progress in their work packages.

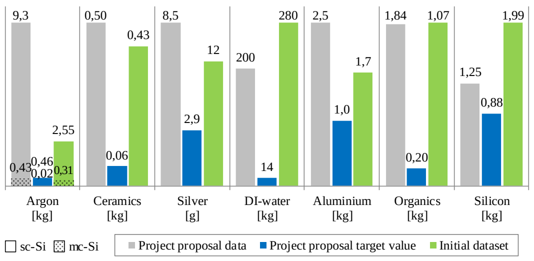

Figure 2: Comparison of proposal targets and initial values at project start

3 STATUS OF SELECTED INDIVIDUAL PROJECT DEVELOPMENTS REGARDING ENVIRONMENTAL IMPACT AND MATERIAL REDUCTION

Basis for the midterm, preliminary LCA are data from the project partners regarding the progress in their work packages. These data were integrated in the material and energy flow model and evaluated. The selection of impact categories for the LCIA (Life Cycle Impact Assessment) has been made by following the ILCD/PEF (International Reference Life Cycle Data System / Product Environmental Footprint) recommendations [6],[7].

3.1 Argon gas recovery

The first step of the value chain included is the production of cz-crystals and multicrystalline ingots. During this process step, pure argon gas, used to remove contaminants, is currently being vented into the air. Though perhaps argon is abundantly available in the earth's atmosphere (approximately 1 % of mass), there are still (ecological and financial) costs involved in the production of pure gas. For instance, the argon consumption in NorSun's wafer facility is responsible for 3-5 % of the wafer cost.

In other industries argon gas recycling has become already state of the art but in PV-production this was not yet the case. A relatively simple and cost efficient technique – developed by GR2L – is based on a chemical looping combustion process to convert combustible species in the exhaust gas stream to carbon dioxide and water, followed by removal of carbon dioxide and water in reclaimable reactor beds. Such a recycling system has been integrated in NorSun's factory collecting and recycling exhaust gas from eight crystal pullers. First results from crystals grown with argon recycling show similar material performance compared to the standard process without recycling.

Environmental impact and material reduction on the example mono-Si based PV module

The approach considers that used argon gas will be treated and afterwards meets the requirement of argon gas for up to 90 % by weight. The data for modelling the argon recovery process are provided by project partner NorSun. The result regarding material reduction shows, that one project target – reduction of argon gas demand to 0.46 kg per PV module – can be achieved totally (see figure 3) by implementing of the argon gas recovery process. Compared with the results of the baseline-scenario environmental, although not large, advantages exist for all examined impact categories. The proportion range goes from 0.1 % for depletion of mineral, fossil and renewable resources to 1.8 % for climate change and depletion of water resources. Saving of over 95 % could be realised if the waste argon is purified and reused and a full implementation of the Ar recovery system is planned.

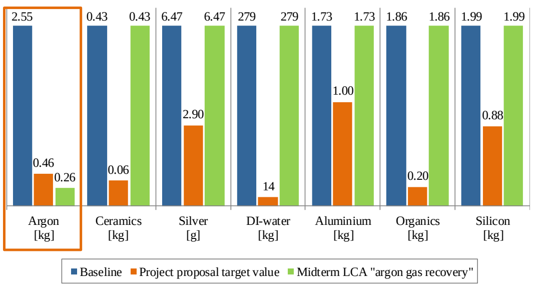

Figure 3: Argon gas recovery - reduction of waste and resource consumption per production of 1 mono-Si based PV-module compared with the baseline process and the project targets.

3.2 New wire sawing process with thinner diamond wire and silicon kerf recovery process from sawing machines coolant

After crystallisation, side-, top- and bottom-parts are cut off before the ingot is cut into blocks and latter wafered. A considerable amount of silicon is lost in form of submicron saw dust (kerf-loss) during squaring and wafer cutting processes. Up to 50 % of the initial silicon amount is lost and can be recovered from the coolant depending on the sawing conditions. In addition to the possibility to use thinner diamond saw wire associated with a decrease in silicon kerf-loss, the ability to recycle the kerf-loss for solar ingot production will have beneficial effects in terms of savings of precious poly-silicon consumption and of waste reduction. Therefore, Garbo has patented and implemented a silicon recycling process which removes contaminations and brings silicon to 99.999 % purity. Purified silicon is then dried, compacted and packed under vacuum in order to obtain a stable silicon powder that, however, might need to undergo a high temperature oxygen degassing process before being used as feed material in the standard production of solar ingots and cells.

The approach considers two aspects:

Firstly a new wire sawing process developed by the project partner Norsun utilises thinner diamond wires (from 80 to 60 µm) and allows more wafers to be sawn out from one brick. The additional yield achieved is about 7.92 %. Further the thinner diamond wire leads to a decrease in silicon kerf and wire waste generation.

Secondly, a newly developed silicon kerf recovery process from sawing machines coolant makes it possible to re-use at least part of the silicon. In the LCA analysis it is assumed that 10 % of secondary silicon from kerf can be added to the necessary silicon demand for wafer production without the need for additional preparation of the secondary silicon during melting. This approach is not recommended for mono-Si wafer production because of high oxygen content and therefore is limited to multicrystalline ingot production. The data for modelling the kerf recovery process are provided by project partner Garbo.

The material reduction result shows, that several project targets benefit of implementing the new sawing process and the recovery process, but with small changes only. Compared with the baseline-scenario the demand of argon gas, ceramics and silicon can be reduced by approx. 18 % and the demand of DI-water by about 1 %. Compared with the results of the baseline-scenario environmental advantages exist for all examined environmental impact categories. The proportion range goes from 0.8 % for depletion of mineral, fossil and renewable resources to 8.2 % for climate change (figure 4).

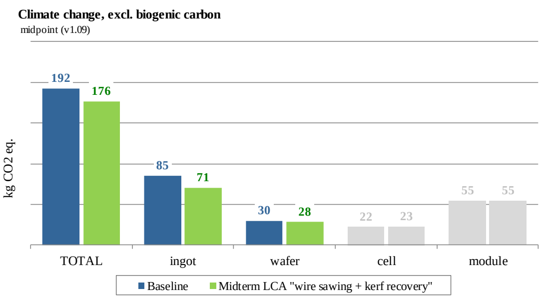

Figure 4: Wire sawing and kerf recovery, climate change – greenhouse gas emissions at the beginning of the project and after implementing a new wire sawing process and a silicon kerf recovery process, calculated for the production of 1 multi-Si based PV-module

Within Eco-Solar, the consortium is looking at three factors on kerf-loss optimisation that will give both environmental and monetary gain. Garbo is working on the reduction of chemicals consumption in Si kerf cleaning step and improving compact density of powders, while Norsun is carrying out sawing tests with increased kerf-loss saturation level in sawing coolant for Garbo to study if (how) the saturation level in the coolant affects the coolant recycling process and the recycled coolant quality.

3.3 New cell process

In crystalline solar cell manufacturing several wet chemical etching and cleaning steps are implemented, which have negative impact on the environmental footprint. By reducing and avoiding certain chemicals or metals and using less pure or recycled chemicals, waste can be reduced and the ecologic footprint of solar cells and panels can be improved.

The approach considers that the standard cell process is replaced by the current status of the cell process at Soli Tek. This cell process is for multi-Si based PV module only. Though better cell efficiencies due to process modifications were obtained no changes in the LCA analysis occurred with respect to material reduction compared to the baseline-scenario, yet. Compared with the results of the baseline-scenario for climate change and depletion of water resources environmental advantages exist amounting to 0.8 % and 2.7 %. The proportion range of the environmental disadvantage goes from 1.7 % for depletion of mineral, fossil and renewable resources to 16 % for eutrophication terrestrial.

Especially silver is an important element, as it is used in most solar cells currently produced, providing the metal contact that "collects" and "drains" the current from the solar cell. In the Eco-Solar project, ISC-Konstanz is developing different solar cell architectures, to minimise the use of silver. In addition, an innovative interconnection scheme enabled by Apollon Solar's module design, avoids soldering of a contact tape onto the rear side silver pads and the front side busbars. Only the small contact fingers on the front side are needed. In addition, ISC-Konstanz and Soli Tek develop an alkaline method for saw damage removal from diamond wire sawing, texturisation and cleaning, that shall replace the current state of art concentrated HF:HNO3, and will investigate advanced processes for emitter formation that will enable higher throughput, resource efficiency and avoid the needs for chemical phosphorous glass layer removal (PSG-removal).

Aimen is working on advanced laser treatment of solar cells, in order to minimize the cut-off area at the wafer edges to a negligible fraction of the whole wafer area, to avoid the wet chemistry normally used to separate the front and rear of the solar cells.

3.4 Usage of an EVA-free glass/glass frameless NICE module (Work package 4 "module design for remanufacturing")

After completion of the cells, they are electrically series connected and assembled into a solar module. As Apollon Solar's NICE-modules are already designed for disassembly Apollon Solar focuses on further reduction of the module BOM (Bill of materials) focussing on a frameless version of the PV module, and integration of electronics in the junction box, to monitor the performance in the field.

The approach considers that the standard EVA laminated modules with front glass and organic backsheet including an aluminium framing shall be replaced by EVA-free glass/glass frameless NICE modules. The data for modelling of a NICE module at the present state of development are provided by Apollon Solar. The material reduction result shows, that one project target – reduction of aluminium demand up to 1 kg per PV module– can be achieved totally. With organics, a second project target benefits as well, but here 74 % of the target value is reached only. Compared with the results of the baseline-scenario environmental advantages exist for all examined impact categories. The proportion range goes from 0.3 % for ozone depletion to more than 55 % for depletion of mineral, fossil and renewable resources. The improvements shown refer to the production step module production only (see figure 5).

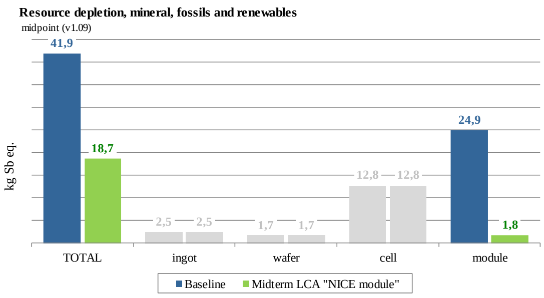

Figure 5: NICE module, resource depletion - consumption of mineral, fossil and renewable resources at the beginning of the project and after replacing the standard EVA laminated module by NICE module, calculated for the production of 1 mono-Si based PV-module

Apollon Solar demonstrates that module assembly of the Eco-Solar cells result in comparable module output as with current (less eco-friendly) state of the art module technology. Furthermore first NICE modules from cells without busbars are made as small laboratory samples for testing and data generation to be used in the LCA. Apollon Solar is working on the disassembly of modules into their major components (glass sheets, copper wires, cells) allowing for their recovery as entire pieces, preserving the value and strong potential for re-use (preferably in PV or other industries).

4 MIDTERM LCA: FIRST EXEMPLARY RESULTS AFTER IMPLEMENTATION OF ALL SELECTED PROJECT DEVELOPMENTS INTO MATERIAL AND ENERGY FLOW MODEL

4.1 Mono-Si based PV module

This approach considers the project developments:

- argon gas recovery,
- new wire sawing process with thinner diamond wire
- and usage of an EVA-free glass/glass frameless NICE module are implemented into the production process chain for a mono-Si based PV module.

The material reduction result shows, that two project targets – reduction of argon gas demand up to 0.46 kg and reduction of aluminium demand up to 1 kg per PV module – can be achieved totally by implementing all project developments. Except demand of silver and DI-water the other project targets benefit as well, but without achieving the target values yet: the demand of ceramics can be reduced by approx. 7.9 %, the demand of silicon by approx. 7.9 % as well and the demand of organics by more than 74 %.

Table 1: Comparison of the environmental burdens and benefits of the impact categories of baseline-scenario and midterm LCA "all project developments" for the production of 1 mono-Si based PV-module (

Impact category	Baseline	Midterm LCA	Environmental impact of midterm LCA compared to baseline
Climate change [kg CO_2 eq.]	316 kg	282 kg	Benefit of 34 kg → 11 % emission reduction
Acidification [Mole of H+ eq.]	2.02 Mole	1.82 Mole	Benefit of 0,21 Mole → 10.2 % emission reduction
Eutrophication terrestrial [Mole of N eq.]	2.92 Mole	2.72 Mole	Benefit of 0,21 Mole → 7 % emission reduction
Ozone depletion [mg CFC-11 eq.]	28.1 mg	26.3 mg	Benefit of 1,8 mg → 6.6 % emission reduction
Photochemical ozone formation [kg NMVOC]	0.91 kg	0.82 kg	Benefit of 0,09 kg → 10.4 % emission reduction
Resource depletion water [m³ eq.]	7.79 m³	6.98 m³	Benefit of 0,81 m³ → 10.4 % resource use reduction
Resource depletion mineral, fossils and renewables [g Sb eq.]	41.9 g	18.3 g	Benefit of 23.6 g → 56.2 % resource use reduction

Compared with the results of the baseline-scenario environmental advantages exist for all examined impact categories. The proportion range goes from 6.6 % for ozone depletion to more than 56 % for depletion of mineral, fossil and renewable resources (see table 1).

4.2 Multi-Si based PV module

This approach considers that the project developments argon gas recovery, new wire sawing process with thinner diamond wire, kerf recovery process, new cell process and usage of an EVA-free glass/glass frameless NICE module are implemented into the production process chain for a multi-Si based PV module.

The result regarding material reduction shows, that one project targets – reduction of aluminium demand up to 1 kg per PV module – can be achieved totally by implementing all project developments. Except demand of silver and DI-water the other project targets benefit as well, but without achieving the target values yet: the demand of argon gas can be reduced by approx. 92 %, the demand of ceramics by approx. 18 %, the demand of silicon by approx. 7.9 % as well and the demand of organics by more than 74 %.

Table 2: Comparison of the environmental burdens and benefits of the impact categories of baseline-scenario and midterm LCA "all project developments" for the production of 1 multi-Si based PV-module

Impact category	Baseline	Midterm LCA	Environmental impact of midterm LCA compared to baseline
Climate change [kg CO_2 eq.]	192 kg	162 kg	Benefit of 30 kg → 15.4 % emission reduction
Acidification [Mole of H+ eq.]	1.31 Mole	1.20 Mole	Benefit of 0,11 Mole → 8.5 % emission reduction
Eutrophication terrestrial [Mole of N eq.]	2.00 Mole	2.16 Mole	Burden of 0,16 Mole → 8.1 % additional emission
Ozone depletion [mg CFC-11 eq.]	16.80 mg	15.44 mg	Benefit of 1.36 mg → 8.1 % emission reduction
Photochemical ozone formation [kg NMVOC]	0.597 kg	0.590 kg	Benefit of 0,007 kg → 1.2 % emission reduction
Resource depletion water [m³ eq.]	3.6 m³	2.9 m³	Benefit of 0,6 m³ → 17.5 % resource use reduction
Resource depletion mineral, fossils and renewables [g Sb eq.]	45.0 g	22.2 g	Benefit of 22.8 g → 50.7 % resource use reduction

Compared with the results of the baseline-scenario environmental advantages exist for all examined impact categories except for eutrophication terrestrial. The proportion range goes from 1.2 % for photochemical ozone formation to almost 51 % for depletion of mineral, fossil and renewable resources. The environmental disadvantage for eutrophication terrestrial is approx. 8 %

due to nitrogen oxide emissions from the new cell process (see table 2).

5 CONCLUSION

The results of the midterm assessment clearly show that some projects targets are already achieved (e.g. Ar gas recycling, reduction of Al consumption) and can be fully implemented. The optimisation of solar cell processes, water consumption and saving and substitution of chemicals has just started. The tests with thinner diamond wires showed the higher yield potential of wafers und minimisation of kerf losses. The reclamation process of kerf is mostly developed and shows the potential of use as secondary feedstock in ingot growing though the relative high oxygen content may limit the share in the feedstock mix or may require a special pre-treatment step.

Europe wants to reduce its needs for raw materials and raise the level of recycling of resources in the solar power industry. Our target is that after the successful completion of this project the greenhouse gas emissions from solar panel manufacturing will be reduced by 25 to 30 per cent and the waste generated will be decreased by 10% minimum.

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