ECO-SOLAR FACTORY: ESTABLISHMENT OF PAN INDUSTRIAL MATERIAL RE-USE OPPORTUNITIES

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ABSTRACT:
The European H2020-FOF-13-2015 Eco-Solar project, that was started in October 2015 envisions to increase resource and energy efficiency over the entire photovoltaic value chain, while simultaneously maximising recycling and remanufacturing possibilities, 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. A pan-industrial approach is used to create an optimized valorisation of by-products, recycled and recovered wastes and mitigate the environmental impacts of PV production and recycling. The best possible utilisation with respect to the eco-efficiency assessment results is identified and novel solutions for poorly recovered and reused materials today will be presented

Keywords: crystalline silicon, eco-efficiency analysis, life cycle assessment, life cycle costing, living lab

1 INTRODUCTION

Eco-Solar is a 3 years H2020 project, which involves 11 partners from 7 member states. Details can be found on the project website: http://www.ecosolar.eu.com.

The target is to identify reuse and recovery routes for the main products and the by-products within the solar and if this will not be possible in other industries. The major material streams are assessed with respect to reuse, remanufacturing, recyclability and utilization of the output for different applications to optimize the eco-efficiency utilizing the Living Lab Methodology. The use of the output may take place in completely different industrial branches. Potential customers and users are invited to test the materials and provide feedback on the experience made. This is done via a living lab, project webpage, trade fairs and conferences.

Eco-Solar aims to develop concepts to improving reuse of resources and components and increasing resource efficiency over the whole value chain. First results on the application of the Living Lab methodology to achieve a better recycling, utilisation and valorisation of by-products and wastes along the PV value chain are presented in 6 examples with a special focus on materials that are valuable or are present in large quantities.

A pan-industrial approach is used to create an optimized valorisation of by-products, recycled and recovered wastes and mitigate the environmental impacts of PV production and recycling. The best possible utilisation with respect to the eco-efficiency assessment results is identified and novel solutions for poorly recovered and reused materials today will be presented

2 AIM AND APPROACH USED

The whole value chain starting with the productions of Czrochalski crystals or multicrystalline Si ingots to the module production was analyzed for by-products and wastes, their quantities, potential values and environmental impacts. First results of the intermediate environmental assessment are presented in a separate paper [1]. Examples of targeted wastes and by-products selected so far are:

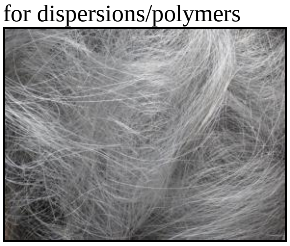
1. <u>ingot production: silica, quartz and silicon nitride crucibles</u> Quartz or silica crucibles are used only once in ingot melting as a current standard practice. Silica crucibles contribute up to ~30% of the conversion cost from Si-feedstock to the as-grown ingot. The used crucibles are usually landfilled, there is hardly any utilisation. Potential utilisations in other industries are under research
2. <u>silicon, silver</u>: silicon cut-offs, broken wafers and solar cells from the production steps like ingot cutting, wafer cutting, solar cell and module manufacturing and end of life treatment, damaged/defective modules, etc. The focus is set on silicon and silver from solar cell processes and recovery because the recovery of silicon is state of the art and there are worldwide specialized companies recycling the material as secondary feedstock or if this is not possible in ceramic or metal alloying applications. Here new potential applications of secondary silicon are targeted.
3. <u>diamond wire from wafer cutting:</u> The wires become thinner and thinner, after cutting hardly any diamonds are present. Several types of wires are used on the market. New solutions of the recycling of the diamond wire are examined.
4. <u>glass sheets and cullet:</u> Glass is usually recycled, only

heavily contaminated fines might be landfilled. Major uses are remelting of the glass in flat glass manufacturing, container glass or glass foam and glass fiber production depending on the quality. Processes to achieve a better quality and new applications of the cullet are investigated.

5. Cu interconnectors from modules: The yield and quality of the Cu interconnectors from recycling processes are examined and improved.
6. Al-frames: The quality and purity of the frames in different recycling processes are assessed to allow a better reutilization.

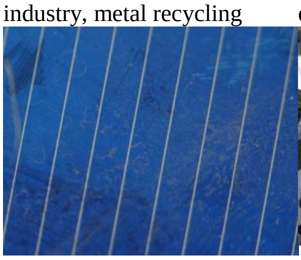
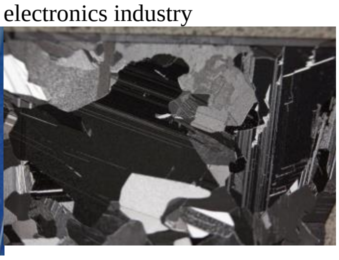
The following pictures give an overview of the mentioned materials and their potential re-uses.


Picture 1 and 2: Silica (left)/quartz (right) crucibles ceramic/glass industry, horticulture, building industry, production of abrasives, ferrosilicon production, additives for dispersions/polymers



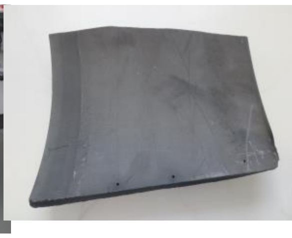
Picture 3: Diamond wire steel industry, diamond industry, metal recycling

Picture 4: Copper wire noble metal recycling, electronics industry

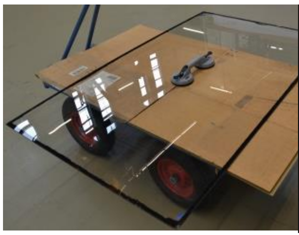



Picture 5 and 6: Retrieved (left)/chemically treated (right) solar cell metallurgy, noble metal recycling, solar cell producer

Picture 7: Wafer sawing slurry possibly containing diamonds metallurgy, metal recycling, organic chemistry (additives), production of abrasives, sawing wire industry, tool industry



Picture 8: Hot zone graphite: additives for ceramic formulas/ dispersions/ polymers/batteries, foundry/steal industry, automobile industry




Picture 9 and 10: Glass sheet (left)/cullet (right) glass recycling, building industry

Picture 11: Al-frame metal industry/ electronics industry

PRELIMINARY RESULTS AND CONCLUSION

Evaluation of crucible re-use opportunities

The silica and quartz crucibles used in the silicon ingot production are currently landfilled in despite of their sufficient quality with regard to possible re-use opportunities. Especially, the horticulture, the production of ferrosilicon, additives for dispersions/polymers and cement/concrete are suitable possibilities.

Table 1: Considerations about the reuse of different crucibles

used quartz and silicon nitride crucibles	***description***
result	high pure silica and silicon nitride crucibles are currently landfilled after use; secondary applications shall be developed for the material
unique selling point	very high purity in comparison to other similar materials
product market size	global market size ~ 50,000 t/a
product positioning	industrial application: ceramic/glass industry, horticulture, building industry, Si-production
requirements (need for authorisations, compliance to standards, norms, etc.)	material has to be modified in order to fulfil the needs of customers
competitors/ incumbents	raw material suppliers
foreseen product price	about 100 €/t
external experts/partners to be involved	silicon smelters, ceramic/glass industry, horticulture, building industry
sources of financing foreseen	savings from landfill costs

Table 2: Analysis of trace elements in a quartz crucible (vitreous $SiO_2 \geq 99.99\%$)[1]

	Al	*15*
Trace elements in ppm	Ca	0.6
	Cr	<0.8
	Cu	<0.3
	Fe	0.5
	K	0.6
	Li	0.7
	Mg	0.06
	Na	0.9
	Ni	<0.03
	Ti	1.3
	OH	30

It can be assumed that similar purity can be achieved with used quartz and silica crucibles after the recycling because the material was in contact with solar grade silicon only. Furthermore, there may still be some silicon residues on both types of crucibles and concerning the quartz crucibles it is obvious that the material went through a phase transformation to β-Cristobalite.
The horticulture is one thinkable re-use of the quartz crucible pieces. As an example, these pieces can be used as a filling material for the so-called gabiones.

Picture 12: Gabione bench filled with used quartz crucibles pieces

Laboratory test results of recycling potential

ICP-OES analytical results of a diamond wire (new and used)
Diamond wire is used for wafer cutting in the semiconductor and solar industry. The diamonds are fixed on the wire with a nickel coating or an organic coating. The project partner Norsun provided samples for the tests. The properties of the used diamond wire are determined by ICP-OES and REM-EDX.

Table 3: Diamond wire metal composition (example, new and used wire, ICP-OES)

element	*New, average value of mass [%]*	*Used, average value of mass [%]*
Cr	1.13	1.17
Fe	83.5	87.3
Ni	15.1	11.5
others	< 0.1	< 0.1

The used diamond wire is expected to be suitable for the reuse in the steel industry. There are experiments in progress to determine a cost-effective treatment in order to remove and to extract the diamonds from the used wire.

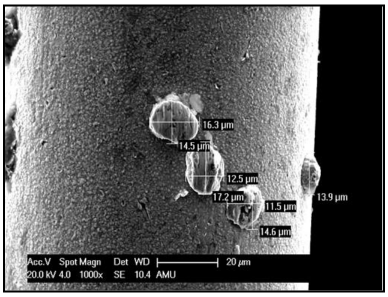


Figure 1: REM of new diamond wire

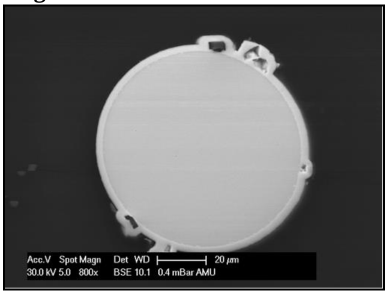


Figure 2: REM cross section of new diamond wire

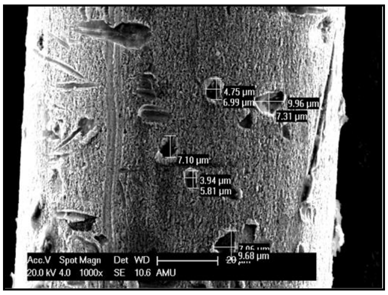


Figure 3: REM of used diamond wire

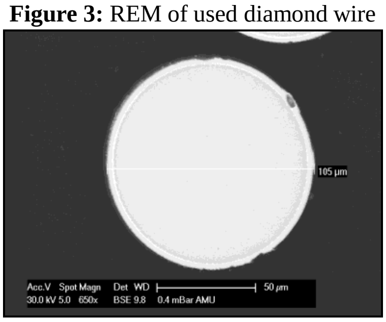


Figure 4: REM cross section of used diamond wire

Analysis of Used Copper Wire
The purity of the used copper wire is 99.93%. Other elements are below the limit of determination and therefore not detectable. The copper wire is analysed by ICP-OES. Copper is the dominant interconnector material but its market share will decrease in the next years due to alternative cell interconnector materials like conductive adhesives which shows lower thermal stresses. These thermal stresses, due to the soldering process, are an issue concerning a direct re-use of extracted copper wires in a new solar module. This material does not fulfil the quality demanded. Concerning the NICE Module this has to be checked.

[1] Source: product data sheet from Saint-Gobain Quartz given by SINTEF

ICP-OES analytical results of an example solar cell composition provided by ISC

Further investigations concerning the solar cells are planned. It is desired to replace the silver on a large scale by a more cost-effective metal like copper. This replacement still demands a lot of research and development and is expected to be introduced step by step in the next decades. By the time being, silver remains the most widely used metallization material in the solar cell production.

Table 4: Metallic components on a solar cell (example)

element	*average value of mass [mg/cell]*
Tl	6.4
Cd	not detectable
Ag	205.8
Al	934.7
Cu	0.4
Pb	4.4

Wafer sawing slurry and diamonds in the slurry

The used slurry from the wafer sawing process contains several components (e.g. diamonds, steel, additives) which may be still valuable if recoverable. In addition, a recovery or even a replacement of metalworking fluids additives is considered as worth for further research. In despite of the re-use opportunities, these additives are potentially toxic for human health and the environment, with long lasting effects to some extent.

Moreover, it can be assumed that most of the diamonds from the wire might be torn out during the sawing process and remain in the slurry. Therefore bifa is examining the slurry in order to find out if a subsequent treatment of the disposed slurry is feasible and cost-effective.

Example: Apollon Solar NICE Module, amount of possible secondary raw materials (Cu, Si, Ag, …)

The waste regulation assessment is based on the data of the NICE Module (BOM, composition, PIB, etc.) delivered by Apollon Solar as well as on the disassembly experiment and the subsequent separation of the compounds at bifa. The definition of appropriate waste streams is the main goal for further considerations concerning recovery/recycling routes and reuse opportunities. Therefore, the quality of the extracted compounds is being examined. Furthermore, the waste streams have to be analysed with respect to hazardous waste criteria. Referring to the state of art modules, some module compounds can be seen as hazardous waste, for instance Cd-containing bus bars or polymers. Therefore, an analysis is taking place in order to confirm the indication that the NICE Module compounds are Cd-free. Identifying the share of the several compounds and allocating the waste key numbers to them is fundamental for the assessment. The definition of the different waste streams is based on the waste regulation. The experiments carried out confirm the assumption of a damage-free disassembly, nevertheless, an automatic disassembly process is crucial in order to compete with new raw materials. The recovery and re-use of intact components seem to be possible. The repair of recovered components such as defective solar cells and subsequent re-use are thinkable but the viability strongly depends on the current cost of new components in comparison with the recovery costs. In addition, the quality requirements will have to be met if a direct re-use is targeted. It is planned to take a closer look on this as a next step.

The compounds of the NICE Module are already allocated to different waste streams. The assessment of each waste stream has been started. It is expected that the new European waste regulation will not be an issue inhibiting reuse and recovery options.

Table 5: NICE PV Module compounds and possible recycling ways (non-exhaustive)

module compound	*material*	*mass [%]*	*possible use of output*
glass	soda-lime glass	30-65	glass industry ceramic industry horticulture building industry
composite material	Acrylate PU	5-10	thermal treatment separation
rear side covering	polyester Al steel glass	0-10 (without glass)	thermal treatment (polymers) plastic recycling metal industry glass industry
frame	Al steel PU PC	0-20	thermal treatment (polymers) plastic recycling metal industry
junction box	ABS, PC, PPO, PET	0-5	thermal treatment plastic recycling
wire	Cu polyolefines synthetic rubber	ca. 1	metal industry wire recycler electronics industry/ recycling
sealant	silicone polyacrylate PE – foam PU	0-10	thermal treatment
filler materials	Al_2O_3, TiO_2, $CaCO_3$, SiO_2, C	ca. 1	fillers mineral additive
solar cells	Si, Ti, Ag, Sn, Pb, Cu, Ni, Pd	5-10	metallurgy solar cell production
electrical connector	Cu, Sn, Pb, Al, Ag	ca. 1	metal industry electronics industry

Hot zone graphite: first customer feedback results

The hot zone graphite is currently used in order to insulate the crucibles during the production of solar grade silicon. As well as the crucibles, the hot zone graphite is used once and landfilled afterwards.

bifa has conducted a survey aiming to find out the requirements and needs of suitable customers of this material. These customers are producers of carbon electrodes, graphite film, polymers (carbon as conductivity additive) as well as members of the foundry and steal industry. As a result, most of these potential customers are interested in the hot zone graphite under certain conditions. A considerable condition is that the hot zone graphite pieces have to be ground to a specific particle size with regard to application. As a consequence, the hot zone graphite has to be treated in advance. The viability of the pre-treatment is being assessed at bifa. Additionally, some prepared samples have been sent to potential customers and results are expected in the near future.

Recovery of solar panel compounds: comparison of current mechanical treatment results

The experiments verify the feasibility of damage-free disassembly of a NICE Module. However, the development of a competitive automatic disassembly to decompose an end-of-life NICE Module into its different components is necessary.

Table 6: Comparison of mechanical treatments

no.	***kind of mechanical treatment***	***recovered materials***	***specific potential value [€/t]***
1	laminated glass recycling plant, incineration in municipal waste incineration plant	Al, glass, Cu	122
2	laminated glass recycling plant, incineration of mono	Si, Al, Ag, glass, Cu	316
3	laminated glass recycling plant, incineration	Solar Si, Al, Ag, glass, Cu	476

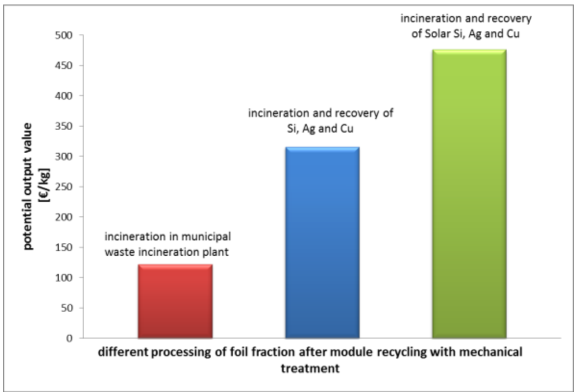


Figure 5: Potential material values after different recycling processes of PV modules

The comparison of mechanical treatments indicates that highly pure outputs of the recycling treatment will increase significantly the value of the secondary raw materials obtained. Moreover, the re-use of secondary raw materials within the solar industry can decrease the cost of solar panels making this kind of renewable energy source even more attractive. In addition, the establishment of a cost-effective treatment may have a positive impact on the eco-efficiency, too.

Table 7: Considerations about the recovery of solar panel compounds

solar panel components	***description***
target	using the state of art solar panel recycling systems in order to generate commercial benefits and to increase the eco-efficiency
result	recovery of solar panel compounds: high yield and high purity desired; secondary applications shall be easily enabled
unique selling point	equal quality for a lower price in comparison to raw materials
product market size	global market size [2] about 43,000 Mt/a
product positioning	industrial application: metal industry, metal recycling, metallurgy, solar cell/panel producer, glass industry, building industry, Si-production
requirements	material has to be modified in order to fulfil the needs of customers
competitors/ incumbents	raw material suppliers, recycling companies
foreseen product price	about 350 €/t
external experts/partners to be involved	laminated glass recycling plant owner, silicon smelters, metal industry, metal recycler, metallurgy, solar cell/panel producer, glass industry, building industry, Si-production
sources of financing foreseen	proceeds from the separated and purified solar panel compounds, using an established laminated glass recycling plant, savings from landfill costs

The question whether there is a subsequent treatment of the disposed wafer cutting slurry is still a challenge bifa deals with. The expectation has to be considered that the throughput is assumed to decline remarkably in the near future. Hence it follows, that the amount of possibly recovered material decreases significantly. Thus the conditions of a recovery or re-use route become a demanding task. Further research and input from project partners are necessary.

[2] IRENA and IEA-PVPS (2016), "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems

Table 8: Considerations about the recovery of wafer sawing slurry containing diamonds

wafer sawing slurry containing diamonds	***description***
target	using the state of art extraction recycling systems in order to generate commercial benefits and to increase the eco-efficiency
result	recovery of fluid, Si and diamonds: high yield and high purity desired; secondary applications shall be easily enabled
unique selling point	equal quality for a lower price in comparison to raw materials
product market size	global market size about >100 kt/**a**
product positioning	metallurgy, metal recycling, organic chemistry concerning additives, production of abrasives, sawing wire industry, tool industry
requirements	slurry has to be treated in order to extract the valuables
competitors/ incumbents	raw material suppliers, recycling companies
foreseen product price	<10 €/kg
external experts/partners to be involved	silicon smelters, metal industry, metal recycler, metallurgy, tool industry, Si-production
sources of financing foreseen	proceeds from the separated and purified slurry, using an established extraction technology, savings from landfill costs

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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