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WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE): A CLOSER LOOK AT PHOTOVOLTAIC PANELS

Dr. Sigrid Kusch[1, 2]

Dr. Mohammad A. T. Alsheyab[3]

[1] University of Padua, **Italy**
[2] University of Southampton, **UK**
[3] Qatar Foundation R&D - QNRF, **Qatar**

ABSTRACT

End-of-life solar photovoltaic (PV) panels represent a waste stream that will show high and rapid increase from 2020 onwards. Annual quantities could rise by a factor of 25 or higher in the period 2020 to 2050, turning waste PV panels into a material stream that will account for a significant share of waste electrical and electronic equipment occurrence. Assessing the types of modules on the market displays a high and further growing variety of PV panels, showing differences in design, basic technology and used components, which poses specific challenges with view to recycling. A compilation of the composition of main PV panel types reveals that standard recycling procedures can be applied to those components that account for the major share of the panel mass (glass, aluminum, polymers, electronics). However, PV panels also contain precious materials such as indium, gallium, tellurium, silver, but they account for very low percentages of the total panel mass. Precious materials warrant increased efforts to implement advanced PV recycling processes that aim at recuperation of low concentrated constituents. At the same time, in particular when managing thin-film PV panels, hazardous components (cadmium, heavy metals) require specific attention.

Keywords: e-waste, solar energy, solar panels, photovoltaic modules, end-of-life management

INTRODUCTION

E-waste, or WEEE (waste electrical and electronic equipment), is a waste stream that needs to be addressed with priority due to its rapidly growing quantities and its contents in both hazardous and precious materials [1-3]. Although there is no standard definition for WEEE, the term generally refers to any electrical and electronic equipment which the owner intends to discard. Any appliance using an electric power connection and which has reached its end of life can therefore be considered WEEE [4].

In the European Union (EU), the WEEE Directive (Directive 2002/96/EC) defines WEEE and sets a framework for its management, including collection and recycling of the waste streams. Since 2014, when the 2012 revision of the WEEE Directive came into force, solar photovoltaic (PV) panels to be discarded fall under the WEEE Directive and are therefore now classified as WEEE in the EU. The directive defines PV panels as pieces of electrical equipment designed to generate electricity from sunlight. The directive sets targets for collection of end-of-life modules in EU Member States, as well as targets for recycling, based on the “Extended Producer Responsibility” (EPR) principle. EPR extends responsibility of the producer (the entity that first placed a product on a national market, e.g. a manufacturer, an importer, a distributor, a retailer) to the collection, recovery and final disposal phases of a product. This life-cycle approach means that in the EU, producers are responsible to set up schemes for collection and treatment of end-of-life PV panels. In regions that are outside of the EU, there is a lack of consistent legislation for managing end-of-life PV modules, and in consequence the individual country’s regulations for general waste treatment apply [5].

Deployment of PV for energy supply started relatively recently (last 1 to 2 decades of 20th century), and the clear majority of modules have been installed after the beginning of the 21st century [5-7]. In consequence, the quantity of waste PV panels is currently still low. However, a huge increase of this waste flow is to be expected in the coming decades [5, 8-10]; the photovoltaic market is characterised by very rapid growth [5, 7]. Increasing efforts are required for a sound management of end-of-life PV panels, in particular with view to recycling [6].

This publication sheds light on the upcoming problem of waste when PV panels reach their end of life phase. It also highlights the increasing need for recycling to limit adverse environmental impacts and to secure secondary resources.

QUANTITATIVE SCALE OF THE CHALLENGE: WASTE STREAMS FROM END-OF-LIFE PV PANELS

Most PV panels were installed in the last years, while first installations date back to the 1990s. Around 30% of the currently installed capacity worldwide was added during the last three years [7], and further fast growth of capacity can be expected in the coming decades (factor 20 from 2015 to 2050 [5]), see Figure 1. Once installed, solar PV panels have a relatively long period of active use, which is typically around 20 to 30 years, or longer [5, 8-10]; therefore, they reach end-of-life and become waste with a significant time shift from the moment of their installation.

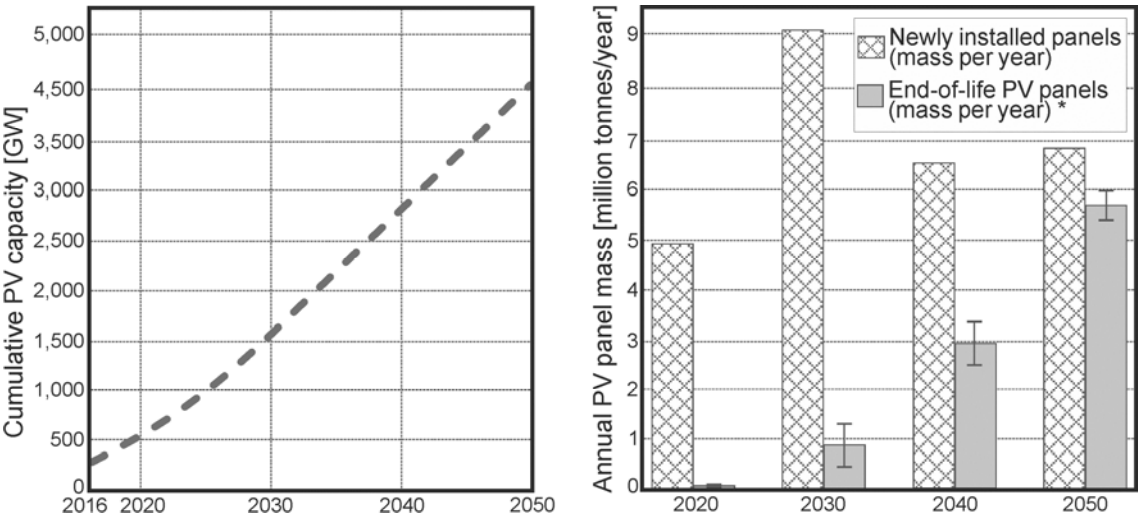

Figure 1 Left: projected cumulative global PV capacity; Right: annual mass flows from PV panels: newly installed panels and end-of-life panels (waste) (* average value of two scenarios, bars indicate low and high value of scenario results) (based on data from [5]; data take into consideration changes in weight of modules over time)

While currently the quantity of end-of-life PV modules is still low (accounting for few parts per thousand of total WEEE generation), PV waste streams are now starting to grow, and will drastically increase in the coming decades (Figure 1). By 2050, global annual PV panel waste could exceed 10% of total WEEE generation [5], representing a huge potential source for the recovery of secondary resources. The data also reveal that, even if recycling was fully implemented, manufacturing of new PV panels will still be relying on utilisation of primary resources for the next two to three decades, since the mass of end-of-life panels will remain considerably below the mass of newly installed ones [5]. Nevertheless, and in particular from 2035 onwards, PV waste recycling can make a significant contribution to reducing the demand for primary resources; it was further estimated that by 2050, the mass flow of end-of-life panels will approach the mass of newly installed panels [5].

TYPES AND COMPOSITION OF PV PANELS

The PV market is dominated by crystalline silicon panels (c-Si; wafer-based) with a share of around 90% (monocrystalline Si panels: 40%, polycrystalline: 50%). The second major type are thin-film panels (10% market share), a category that comprises different types of PV cells (Table 1). The common characteristic is that thin-film cells are manufactured by applying thin layers of materials onto a carrying substrate, while c-Si solar cells are manufactured by cutting slices from silicon crystals. Thin-film panels are more resource efficient (lower resource consumption) compared to c-Si panels. The two main thin-film types today are CdTe and CIGS (including CIS; predominant:

copper indium gallium diselenide cells), while a-Si panels were installed in the last two decades, but are now losing market importance due to their low efficiencies.

Table 1: Current and future market share of PV panels (partly based on [5, 10], amended)

Technology type	Solar cell basis	2014	2020	2030
Crystalline silicon panels (c-Si), using wafers 120-200 µm	Monocrystalline Si; poly-/ multicrystalline Si	90%	73%	45%
Thin-film technology, using thin layers (few µm) of semiconductors	a-Si/ µ-Si (amorph/ micromorph silicon)	< 3%		0%
	Cadmium telluride (CdTe)	5%	5%	5%
	Chalcopyrite materials [CIS: $CuIn(S,Se)_2$; CIGS: $Cu(In,Ga)(S,Se)_2$]	2%	5%	7%
Novel/ emerging technologies (includes novel thin-film types)	CIGS alternatives, CZTS, CZTSe: Cu_2ZnSnS_4, $Cu_2ZnSnSe_4$; perovskites	< 1%	1%	9%
	Next-generation c-Si (thin-film)	< 1%	9%	26%
	Organic cells; dye-sensitized cells; polymers	< 1%	6%	9%

Table 1 outlines that diversity of panels on the market will further increase in the coming decades. Novel technologies include: (1) advanced c-Si solar cells, e.g. based on nanotechnologies, with higher efficiencies and less resource consumption (thin-film types); (2) solar cells that are similar to CIGS cells, but substitute the critical resources indium (In) and gallium (Ga) by more common elements such as zinc (Zn) and tin (Sn); (3) perovskite solar cells, with a specific crystal structure (perovskite structure – often a mixture of organic and inorganic constituents) of the high-efficient absorber materials; (4) organic solar cells; (5) dye-sensitized solar cells; (6) polymer solar cells. Overall, silicon based modules will remain dominant on the market, but with growing diversity. At the same time, thin-film panels will gain importance, and will increase their variety as well. When considering the fact that installed PV capacity will significantly increase in the coming decades, it becomes evident that the absolute numbers of PV panels to manage will considerably grow – both of newly installed panels and end-of-life panels, including thin-film modules. Sound waste management and recycling will need to address both growing quantities and increasing diversities of PV panels.

Solar cells contain light absorbing active components (semiconductors) that convert the energy of light into electricity by the photovoltaic effect, but also components that improve functionality, enable electric connectivity of the device, ensure stability and connect the components together. PV panels constitute of solar cells, but also of components that enable installation of the modules (e.g. aluminium frames) and electrical connection (e.g. cables, electronics), components that serve for protection against weather impacts (e.g. glass sheets), and components that ensure stability of the elements and cohesion of the assemblage (polymer layers, adhesives). Used materials and quantities differ among the panel types (Table 2).

Table 2: Average composition of currently installed PV panels, in percentage of total panel mass (best possible estimate, based on [8-14] and amended by market research)

	c-Si	a-Si	CIGS	CdTe
Glass	ca. 75%	ca. 85%	ca. 85%	ca. 95%
Aluminium (Al)	ca. 10%	ca. 10%	ca. 8%	< 0.01%
Silicon (Si)	ca. 5%	< 0.1%		
Polymers (plastics, films, adhesives)	ca. 8%	ca. 5%	ca. 5%	ca. 3%
Copper (mainly cables) (Cu)	ca. 0.8%	ca. 0.5%	ca. 0.8%	ca. 0.9%
Lead (Pb)	< 0.1%	< 0.1%	< 0.1%	< 0.01%
Zinc (Zn)	ca. 0.15%	< 0.1%	ca. 0.12%	ca. 0.02%
Selenium (Se)			ca. 0.03%	
Cadmium (Cd)			< 0.01%	ca. 0.08%
Tellurium (Te)				ca. 0.08%
Indium (In)		< 0.002%	ca. 0.02%	
Gallium (Ga)			ca. 0.01%	
Molybdenum (Mo)			ca. 0.05%	ca. 0.05%
Silver (Ag)	ca. 0.005%			ca. 0.01%

Bulk materials are glass, aluminium (frames) and polymers. However, among the materials with low shares, both hazardous and precious materials are to be found. A variety of heavy metals (Pb, Cd, Cu, Zn, Se, others) as well as components with wider toxicological risks (in particular Cd is carcinogenic) induces a hazardous potential of end-of-life PV panels, which is clearly more pronounced for thin-film panels.

Among the materials with particularly high economic importance are indium, gallium, tellurium and silver, all of which are present in very low concentrations (below 0.1% of total panel mass). Despite its low concentration, silver accounts for nearly 50% of the economic material value of c-Si panels [5]; use of Ag is expected to decline in future, but the PV industry currently consumes around 1,400 tonnes per year, which is 5% of global Ag production in 2015 [15]. For manufacturing of thin-film panels, tellurium is one of the components difficult to substitute, characterised by high risk of availability, and particularly high importance in the PV sector [10, 13]. Furthermore, indium and gallium are of particularly high strategic and economic importance [5, 13, 15], and were included in the list of the 20 “critical raw materials” for the EU – materials that were identified as vital in the context of the future development of the EU economy and at the same time characterised by high risk of supply and low substitution potential.

RECYCLING OF END-OF-LIFE PHOTOVOLTAIC PANELS

Recycling of PV panels, implemented at high quality, would ideally aim at avoiding loss of both conventional resources (glass, aluminium) and rare elements (silver, indium, gallium, tellurium), while at the same time ensuring sound management of hazardous materials (contained in panels or needed in the recycling process).

Bulk constituents such as glass, metal frames, electronic components, organic components largely become easily available after simple dismantling of the PV panels, which facilitates their diversion towards recycling schemes. Established standard technologies are available for treating the bulk constituents (Table 3), while recuperation of low-concentrated materials from the inner core of solar cells requires specialised combination processes, including methods to release the materials from the tight assembly prior to further treatment.

Table 3: Key valorisation options for PV panel components

Component	% by weight	Recycling/ Valorisation	Product	Degree of challenge
Glass	70-95	Glass recycling	Flat glass, hollow glass, glass wool, foam glass	Well-established, but risk of downcycling
Frame [1)]	0.x-10	Metal recycling	Standard products	Well-established
Cables, electron. comp.	1-3	Electronic scrap recycling, metal rec.	Standard products	Well-established
Polymers [2)]	3-15	Thermal treatment	Energy	Well-established
“Core area” of c-Si solar cells	4-6	Special processes (target components: Si, Ag, etc.)	Secondary res. (solar cell prod., metals, alloy materials)	Combination procedures required [3)]
“Core area” of thin-film solar cells	< 1	Special processes (target comp.: In, Ga, Te, Cd, Mo, etc.)	Secondary resources (solar cell prod., other use)	Extended comb. procedures required [4)]

1) Aluminium, partially also stainless steel

2) Embedding layers, carrier materials, films, sheets, adhesives, sealants

3) Focus thermal methods (break cohesion of assembly) in combination with physical/ mechanical methods; and chemical methods to remove undesired layers from wafers

4) Focus wet-chemical methods, combined with physico-chemical and mechanical methods

Today, specialised PV panel recycling at commercial scale is applied for CdTe thin-film modules by the producer (*First Solar*). Implementing IPR (individual producer responsibility), the producer takes back discarded modules of its own brand and operates recycling facilities at sites where new panels are produced, which enables common treatment of end-of-life panels and production residues. Treatment takes place in different steps, with a focus on wet-chemical methods. Recuperated components (Cd, Te, glass) can be used in the production of new panels.

For other brands, in regions where PV panel collection schemes exist (such as EU countries), the panels are usually collected together for further treatment. The vast majority of collected panels currently enters existing well-established general recycling pathways, in particular goes to conventional glass recycling plants. This achieves recycling of bulk components; however, it does not allow for recuperation of components with low concentration (Si, rare metals), and hence such components usually get lost. In addition, downcycling occurs in particular for glass, the major constituent of PV panels, as contamination results in loss of quality of the material and consequently in manufacturing of products for thermal insulation (glass wool, foam glass) instead of flat or hollow glass.

Specialised PV panel recycling plants aiming at recycling of panels of different brands are at pilot stage, and have been or are successfully operated for either Si-panels (example: *Sunicon* in Freiberg/ Germany) or thin-film panels (examples: *Saperatec* using an ecological cocktail of tensides to break down the close assemblage of valuable components in thin-film modules; *Loser Chemie* using acid baths).

Currently, reaching economic viability of specialised PV panel recycling is still challenging, although a variety of technologies have been explored and are principally useable [6]. Rare metals combined typically only represent 1% of total panel mass, but their value is significant; their recuperation therefore provides a potential pathway to improved economic viability of specialised PV recycling technologies [5, 6, 13]. One factor in this context is that throughout the last decades the quantities of end-of-life panels were too low to allow commercial operation of such facilities [10, 13]; in the coming decades, increasing waste flows will foster economies of scale [5].

A prerequisite for achieving sound management of end-of-life PV panels is the establishment of effective collection schemes. While in EU countries this is ensured by the implementation of EPR through the regulations of the WEEE Directive, there is a lack of effective regulation in other regions. EPR-schemes also facilitate that the costs of sound treatment of end-of-life panels is taken into account under a life-cycle perspective, which is favourable with view to commercial operation of dedicated specialised recycling facilities.

Many countries and regions still face the challenge to establish effective legal frameworks as well as the required infrastructures for sound WEEE management [3]. Among others, the level of awareness and reaction on WEEE occurrence differs significantly between developed and developing countries. Clearly, consideration of PV waste already when establishing basic WEEE management schemes is suitable; this highlights the need to clearly classify end-of-life PV panels as WEEE, as pioneered by the EU regulation, to overcome the situation where in many countries such panels still fall under the general waste management schemes.

CONCLUSION

The booming photovoltaic industry will be accompanied by an increasing demand for resources in the coming decades. From 2020 onwards, rapidly growing amounts of end-of-life panels will occur as a further companion of PV deployment. This solid waste represents both an emerging problem that needs to be addressed and a material stream that warrants increased attention due to constituents with high economic value.

The waste consists of three main streams: (1) conventional materials such as glass and aluminium; (2) rare materials such as silver, indium, gallium and tellurium; and (3) hazardous elements such as lead, cadmium, selenium and other heavy metals.

While recycling of conventional components such as glass and aluminium is useful to limit adverse environmental impacts of PV exploitation, in particular through securing secondary resources, recycling becomes indispensable for the recovery of rare metals that are vital for positive further performance of economies, including those rare elements which belong to the EU list of the 20 critical raw materials. Although rare materials form only 1% of the total panel mass, their economic value is quite significant, which provides an opportunity to improve economic viability of advanced recycling schemes. The toxic and harmful materials must be separated and properly managed.

To achieve sound management of end-of life PV panels, establishment and operation of effective collection schemes is an essential prerequisite.

More research and development is needed to assess the potential recovery of different components of the end-of-life PV panels and to advance economic viability of recuperation of rare elements.

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