Life cycle management and recycling of PV systems

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Abstract

Future waste volumes related to exponential growth in photovoltaic (PV) system deployment pose both a waste management challenge and resource recovery opportunity for the PV industry. Active international R&D projects and patent activity have identified mechanical, thermal, chemical and optical methods to delaminate PV modules and extract glass and metals. In addition to lab-scale research, First Solar has demonstrated high-value recycling technology and continuous improvement at a commercial scale. Through implementation of the WEEE Directive, Europe has created the first mandatory market for PV module recycling including the development of PV-specific waste handling and treatment standards. As PV system component prices continue to drop, the financial provisions related to decommissioning, collection and recycling become more relevant to the levelized cost of electricity for PV generation assets. Recent economic analysis indicates that the commercial scrap value of PV power plant decommissioning exceeds decommissioning costs by up to US$0.01-0.02 per watt, further incentivizing recycling over disposal.

Introduction

In 2015, estimated annual global volumes of electronic waste (e-waste) reached a record 43.8 million metric tons and global e-waste generation is expected to increase up to 50 million metric tons by 2018 [1]. Even though solar PV panels significantly differ from typical consumer electronic products, global regulators view PV panels increasingly in the context of e-waste regulations. Solar PV currently accounts for less than 1% of total annual e-waste volumes. However, as PV deployment continues to grow exponentially, cumulative PV waste is expected to amount to 1.7 million-8 million metric tons by 2030, equivalent to 3-16% of total e-waste produced annually today [2]. As global PV demand increases and more modules and systems reach the end of their useful life over the next 10-15 years, recycling will become increasingly important for all PV technologies to ensure that clean energy solutions do not pose a waste burden.

In addition to ensuring compliance with evolving regulatory waste management requirements, PV recycling offers an opportunity to influence project economics in an increasingly commoditized market. As component prices continue to drop, the financial provisions related to decommissioning, collection and recycling become more relevant to the levelized cost of electricity (LCOE) for PV generation assets. These provisions have to be taken into consideration during PV project development, site permitting and when putting PV system components on the market (i.e. PV modules, inverters, other electrical and electronic products).

Voluntary and regulatory approaches to end-of-life management in leading markets

In most countries, PV panels are classified as general or industrial waste and managed in accordance with general waste treatment and disposal requirements [2]. Beyond general waste regulation, voluntary and regulatory approaches have been specifically developed for managing end-of-life PV waste.

The European Union (EU) was the first to adopt PV-specific waste regulations by mandating the recycling of all solar panels under the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU). Since 2012, the provisions of the WEEE Directive have been transposed into national law by the EU member states, creating the first mandatory market for PV module recycling. In the United States, PV panel disposal is covered under the Resource Conservation and Recovery Act, which is the legal framework for managing hazardous and non-hazardous waste. In 2016, the US Solar Energy Industries Association (SEIA) partnered with PV manufacturers and installer-developers to voluntarily launch a national PV recycling programme, which aims to make affordable PV recycling solutions more accessible to consumers [3].

In Japan, end-of-life PV panels are covered under the general regulatory framework for waste management (the Waste Management and Public Cleansing Act), which defines industrial waste generator and handler responsibilities and waste management requirements including landfill disposal. In 2015, a roadmap for promoting a scheme for collection, recycling and proper treatment of end-of-life renewable energy equipment was developed, followed in 2016 by a guideline promoting proper end-of-life treatment of PV modules including recycling [2].

China has no PV-specific waste regulations but has sponsored R&D on PV recycling technologies through the National High-tech R&D Programme for PV Recycling and Safety Disposal Research under the 12th five-year plan. Directives for

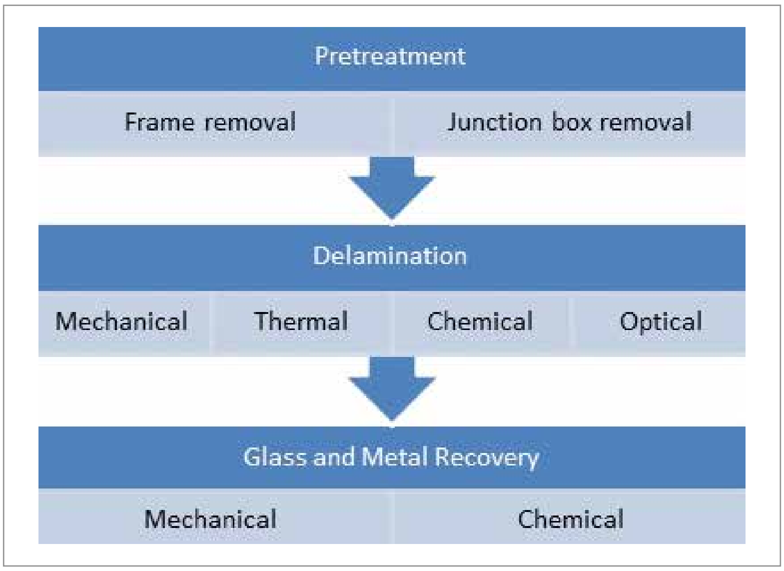

Figure 1. High value PV recycling process steps.

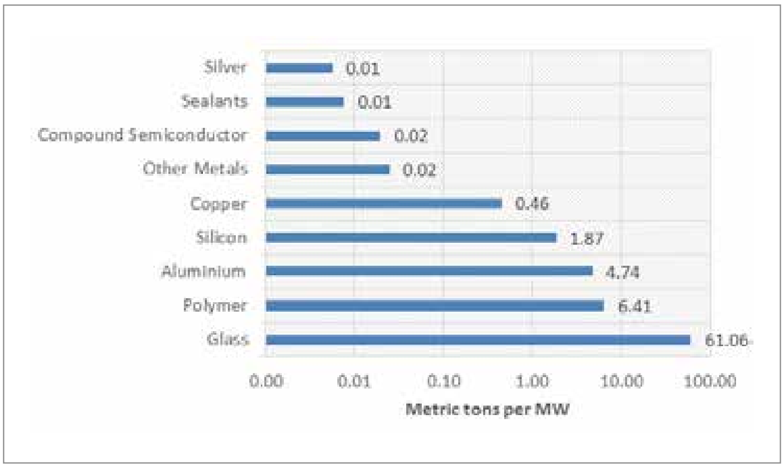

Figure 2. Average recoverable material fractions of PV Panels in 2030 based on [2].

accelerating the end-of-life management of waste PV modules are also expected in the 13th five-year plan. In India, PV waste is managed by the Ministry of Environment, Forest and Climate Change under the 2016 Solid Waste Management Rules and the Hazardous and Other Wastes (Management and Transboundary Movement) Rules [2].

Internationally, a new sustainability leadership standard for PV modules (NSF 457) includes product end-of-life management criteria covering take-back and recycling.

PV recycling technology

In recent years, R&D projects on PV recycling technology have been sponsored in Europe, China, Japan and Korea, and there has been significant patent activity for both crystalline silicon (c-Si) and thin-film PV module recycling technology in the same regions as well as in the United States [4]. Recycling technology can be categorized as either bulk recycling (recovery of high-mass fraction materials such as glass, aluminum and copper) or high-value recycling (recovery of both bulk materials and semiconductor and trace metals). Bulk recycling is similar to existing laminated glass recycling technology in other industries, and may not recover environmentally sensitive (e.g., Pb, Cd, Se) or valuable (e.g., Ag, In, Te, solar-grade Si) materials in PV modules. High-value PV recycling consists of three main steps: pretreatment to remove the metal frame and junction box, delamination to remove the module encapsulant and recovery to extract glass and metals from the module (Figure 1).

Some common goals in PV recycling technology are to maximize recovery yields, minimize impurities in the products of recycling and minimize capital and operating costs to be competitive with other disposal options. Ensuring worker safety and environmental protection are additional priorities that are implemented through management systems such as OHSAS 18001 and ISO 14001, and air emissions controls and wastewater treatment technology.

In addition to technology, other related considerations that affect the viability of PV recycling are effective collection schemes, predictable waste volumes, customers for the products of recycling and regulations on the handling and transport of waste. These factors can affect commercial decisions on when and where to site PV recycling facilities and whether to operate them in a centralized or decentralized (mobile) manner [5].

The recovery value of a PV module

PV panels typically consist of glass, aluminum, copper and semiconductor materials that can be successfully recovered and reused at the end of their useful life (Figure 2). By mass, today's typical crystalline silison PV panels consist of approximately 76% glass, 10% polymer (encapsulant and backsheet foil), 8% aluminium, 5% silicon semiconductor, 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals including tin and lead. Thin-film CIGS and CdTe PV panels consist of higher proportions of glass: 89% and 97%, respectively [2].

Current PV waste volumes remain low as modules have a lifetime of 25 years or more. However, as global PV deployment continues to grow and more modules reach the end of their useful life over the next 10-20 years, PV waste is set to increase nearly 40-fold by 2030 under a normal loss scenario, which assumes a 30-year module lifetime. Leading solar markets including China, the US, Germany, Japan and India (Figure 3) are expected to represent the majority of these projected PV waste streams [2].

By 2030, the recoverable value from recycling end-of-life PV modules is estimated to amount to US$450 million. The recovery value of glass alone has the potential to exceed US$28 million, assuming an average secondary material market price of US$30-50/mt depending on recovery quality of the glass [6].

In Europe, the current raw material recovery rate for recycling PV modules is 65-70% by mass and is in line with the EU WEEE Directive. CENELEC, the European Committee for Electrotechnical Standardization, has developed a supplementary standard specific to PV panel collection and treatment (EN50625-2-4 & TS50625-3-5) to assist treatment operators. The standard specifies various administrative, organizational and technical requirements aimed at preventing pollution and improper disposal, minimizing emissions, promoting increased material recycling and high-value recovery operations, and impeding PV waste shipments to facilities that fail to comply with standard environmental and health and safety requirements. The standard includes specific depollution requirements whereby the content of hazardous substances in output glass fractions shall not exceed the following defined limit values:

- 1 mg/kg (dry matter) cadmium (Si-based PV); 10 mg/kg (dry matter) cadmium (non-Si-based PV)
- 1 mg/kg (dry matter) selenium (Si-based PV); 10 mg/kg (dry matter) selenium (non-Si-based PV)
- 100 mg/kg (dry matter) lead

The residual value of a PV system at end-of-life

Decommissioning cost modelling

Decommissioning a PV system at end-of-life involves dismantling and disposing of the system. For utility-scale PV projects, local permitting requirements often include stringent decommissioning and land remediation measures [7] [8]. These specify disconnecting the project from the grid, removing the installed features (modules, trackers, electrical wire, inverters, transformers, fencing, O&M building, etc.), and recontouring and revegetating the land to its preconstruction condition. For example, the following utility-scale PV projects in the US and Germany have decommissioning plans containing detailed cost estimates for dismantling, disposal and site restoration.

- Desert Stateline Solar Farm Project (300 MW_{AC} PV project in California) [7];
- Helmeringen I Solar Park (10 MW_{AC} PV project in Germany) [8];
- Silver State South Solar Project (250 MW_{AC} PV project in Nevada) [9].

Costs from these and other representative projects can be aggregated and used to model the present value of the net cost to decommission a PV power plant (NDC_{PV}):

$$NDC_{PV} = \frac{[(DC_T + IC_T + MR_T + LF_T) - SV_T - LV_T]}{(1+r)^T}$$

where,

$DC_T + IC_T$ = Direct cost (labour, equipment) and indirect cost of PV plant de-installation, demolition, recovery, and land reclamation in year T.

MR_T = PV module recycling cost in year T.

LF_T = Landfill disposal cost in year T, including landfill tipping fees and hauling, of non-salvageable material.

SV_T = Scrap value of steel, copper and aluminum recovered during PV solar field and power equipment removal and sold to recyclers at prices prevailing in year T.

LV_T = Value of reclaimed land in year T.

r = Rate of annual discount applied to costs and revenues realized in year T.

In order for net costs to be negative (profitable), the scrap metal value and/or land value must exceed the decommissioning costs. In particular, there are large quantities of steel, copper and aluminum in PV power plants (Figure 4) associated with mounting structures and electrical cables.

Recent economic analysis indicates that the commercial scrap value of PV power plant decommissioning (mainly associated with scrap steel and copper) exceeds decommissioning costs, incentivizing recycling over disposal. Decommissioning cost optimization modelling by Fthenakis et al. [11] estimated a net profit of up to US$1.58 per module area. Monte Carlo analysis by ERM [12] indicated 100% confidence in a net profit from PV plant decommissioning when land value was included and up to 95% confidence in a net profit when land value was excluded, depending on plant design scenarios such as above-ground versus below-ground cabling. High-value recycling scenarios in both studies indicate opportunities to positively influence project economics and the LCOE of a given PV project, with net revenues of up to US$0.01-0.02/W from project decommissioning (excluding land value).

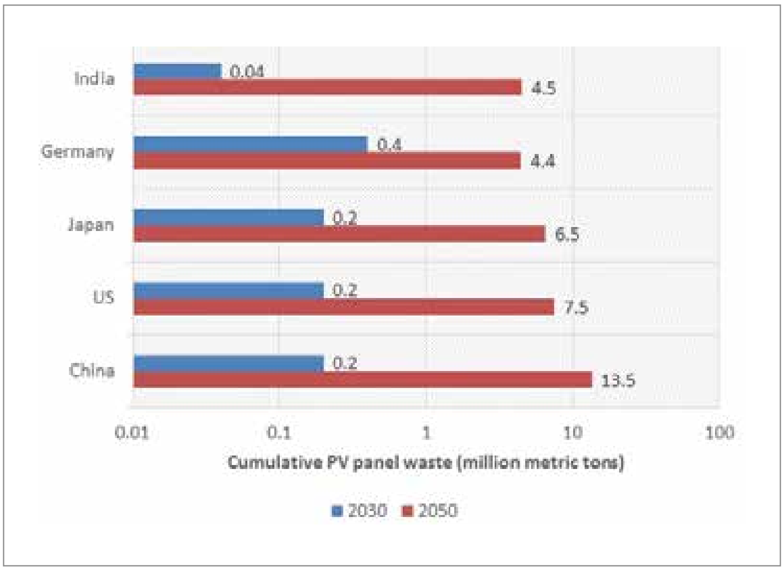

Figure 3. Estimated cumulative PV waste volumes in leading solar markets by 2030 and 2050 (regular loss scenario) [2].

State-of-the-art: the First Solar recycling process

In 2005, First Solar established the industry's first voluntary global module recycling programme and

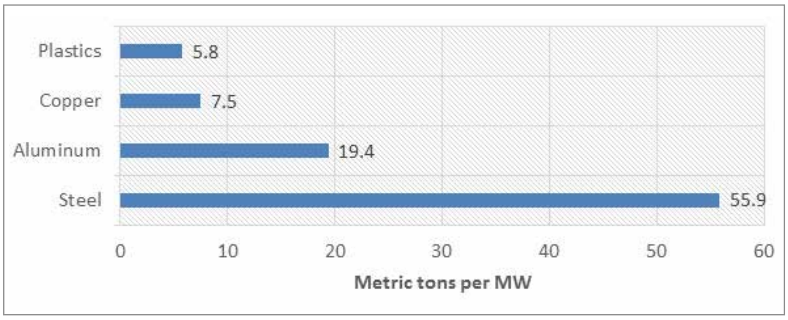

Figure 4. Material fractions of PV power plants [10].

Figure 5. First Solar's first-generation recycling technology based on the mining industry's batch process.

Figure 6. First Solar's second-generation recycling technology based on the chemical industry's batch process.

has been proactively investing in recycling technology improvements and driving down recycling costs ever since (figures 5-7). In contrast to mechanical recycling processes which focus on recovering major components such as glass, copper and aluminum, First Solar's high-value recycling process is able to recapture more materials while retaining their maximum value so they can be reused in new First Solar modules and new glass or rubber products. First Solar's state-of-the-art PV recycling process recovers more than 90% of the semiconductor material and approximately 90% of glass.

First Solar's first-generation recycling technology was based on the mining industry and involved moving glass and liquid from process to process with a modest 10 metric tons per day capacity. In 2011, First Solar developed its second-generation recycling technology, which was based on the chemical industry batch process of circulating liquids within scalable reactor columns (30 metric tons per day capacity).

In 2015, First Solar developed its third-generation recycling technology which achieves superior glass and semiconductor purity with reduced capital and operating (chemicals, waste and labour) costs. The continuous-flow process improves the recycling efficiency and throughput, increasing the plant's daily recycling capacity from 30 metric tons to 150 metric tons.

First Solar is proactively investing in recycling technology improvements to drive down overall PV waste collection and recycling costs. By 2018, First Solar recycling plants will have zero liquid waste discharge and will convert most of the incoming PV waste streams into valuable raw materials for other industries.

Conclusions

The responsible life cycle management of PV systems is not only becoming a compliance requirement, e.g. in the European Union where PV module recycling is already mandated by the EU WEEE directive, but also offers opportunities to positively influence project economics and the LCOE of a given PV project by leveraging cost-effective, high-value recycling technologies. In addition to creating value from secondary resources, PV recycling services help de-risk the decommissioning and end-of-life phase for PV asset owners.

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Figure 7. First Solar's third-generation PV recycling technology based on a continuous-flow process.

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