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Chapter 2

EVALUATION OF POTENTIAL HEALTH AND ENVIRONMENTAL IMPACTS FROM END-OF-LIFE DISPOSAL OF PHOTOVOLTAICS

Parikhit Sinha[1,*], V. Lyle Trumbull[2], Swiatoslav W. Kaczmar[3] and Keith A. Johnson[4]
[1]First Solar, Tempe, AZ, US
[2]O'Brien & Gere, E. Norriton, PA, US
[3]SUNY Upstate Medical University, Syracuse, NY, US
[4]Tetra Tech BAS, Phoenix, AZ, US

Abstract

Global solar photovoltaic (PV) deployment has enjoyed exponential growth in the past decade and as the industry grows, large future end-of-life PV waste volumes will need to be managed. It is likely that recycling will be a dominant strategy as in the case of the European Union, where end-of-life collection and recycling will be mandatory beginning 2014 under the recast Waste from Electrical and Electronic Equipment Directive. However, PV deployment is globalizing beyond the European Union into emerging markets. Given the presence of various metals in PV modules, some stakeholders have raised concerns regarding potential environmental impacts if PV modules are disposed of in unlined landfills instead of sanitary landfills or instead of being recycled. Potential adverse health or environmental impacts associated with disposal of utility-scale (25 MWac) volumes of PV modules in an unlined landfill were evaluated by fate and transport modeling using U.S. EPA Delisting Risk Assessment Software (DRAS). Estimated surface and groundwater media concentrations of Cd and Pb, and associated cancer risks and non-cancer hazards were below human health and ecological screening limits. The hazard index under basic landfill conditions was an order of magnitude lower than under acidic conditions, which is notable as landfills have predominantly neutral to slightly basic conditions over their lifetime. Estimated environmental concentrations of Pb from crystalline silicon PV were comparable to concentrations of Cd

*E-mail address: parikhit.sinha@firstsolar.com.

from cadmium telluride PV, indicating that responsible disposal is important for all PV technologies. Potential impacts may be further limited by use of sanitary landfills or with high value recycling, with the latter providing the important benefit of resource recovery. The DRAS default assumption is Toxicity Characteristic Leachate Procedure (TCLP) data for waste with a fragment size of 1 cm. Experimental crushing of cadmium telluride PV modules in landfill conditions was conducted to evaluate the representativeness of the leachate data used in the DRAS modeling. On average approximately three-quarters of the crushed module fragments were larger than 1 cm, and 99% of module fragments were larger than 0.1 mm. The glass-laminate-glass bond of individual broken module fragments was maintained, and when analyzed without further size reduction, the landfill fragments are non-hazardous based on TCLP and Soluble Threshold Limit Concentration (STLC) testing.

Introduction

Global solar PV deployment has enjoyed exponential growth in the past decade. As the industry grows, PV module recycling is important to managing large future end-of-life waste volumes and conserving raw materials for use in new PV modules. In the European Union (EU), where global PV deployment has historically been concentrated, end-of-life collection and recycling will be mandatory as of 2014, resulting from the inclusion of PV in the recast Waste from Electrical and Electronic Equipment (WEEE) Directive [1]. However, PV deployment is globalizing beyond the EU into emerging markets where a combination of high solar irradiation and unmet and growing demand for electricity can create economically sustainable markets for PV. In these new markets, end-of-life collection and recycling may be achieved voluntarily through PV manufacturers or third party services, or may be mandated in future WEEE-type regulations or through project decommissioning requirements.

It is likely that recycling will be the dominant strategy used to manage future end-of-life waste volumes of PV modules. However, given the presence of various metals in silicon (Si) and cadmium telluride (CdTe) PV modules, some stakeholders have raised concerns regarding potential environmental impacts if PV modules are disposed of in unlined landfills instead of sanitary landfills or instead of being recycled. This concern has been evaluated in this study using a combination of experimental analysis and fate and transport modeling with the U.S. EPA Delisting Risk Assessment Software (DRAS) [2].

In the case of the metal Cd which occurs naturally in Zn, Pb and Cu ores and in coal and other fossil fuels, major industrial releases have been due to waste streams and leaching of landfills, and from a variety of operations that involve cadmium or zinc [3]. For example, there were well documented releases of Cd from Zn mining and smelting operations in the Toyama Prefecture of Japan in the early to mid-twentieth century. With respect to landfills, the disposal of NiCd batteries has been reported to have caused an increase of Cd concentrations in municipal solid waste landfills [4]. Cadmium content in NiCd batteries is in the form of Cd and $Cd(OH)_2$, materials which are less stable and more soluble than the CdTe semiconductor material considered in this study [5].

Potential impacts from landfill disposal of CdTe PV modules have previously been evaluated by Tvermoes et al. using DRAS [6]. Assumptions applied by Tvermoes et al. include landfilling of a large initial waste volume (5,600 kg Cd – corresponding to an 80 MWac project), and continuous disposal of CdTe modules over the active life of landfill (i.e., 1,225 kg Cd per year from years 2 through 20 corresponding to a total of approximately 350 MWac). Other conservative assumptions built into the DRAS model are that the landfill is

unlined and is operating under acidic (fermentation) conditions for the life of the landfill. In reality, landfills have predominantly neutral to slightly basic (methanogenic) conditions over their lifetime [7]. Under these conditions, metal ions are rendered immobile by the formation of metal sulfides. Metal mobility in landfills is also limited by physical mechanisms such as sorption onto clays, silts, and ferrous complexes.

In this evaluation, the DRAS model was used to provide an estimate of potential health and environmental impacts associated with the disposal of end-of-life PV modules in unlined landfills, under conditions more typical and representative of existing and planned utility-scale PV projects. The evaluated scenarios are based on a one-time disposal of a waste volume corresponding to a median size utility-scale PV project, 25MWac, and consider Si PV modules that utilize Pb solder as well as CdTe PV modules. Note that although this study considers utility-scale PV, the waste volume considered is equivalent to that from numerous smaller scale PV systems (e.g., one thousand 25 kW systems). In addition, this study considers the influence of increases in pH that typically take place within a landfill over time with the progression of short-lived fermentation conditions to long-lived methanogenic conditions which limit the mobilization of metals from a typical PV module. Leachate concentrations, which are key inputs to the DRAS model, are also evaluated in this study through a landfill experiment. In sum, the objective of this study is to investigate the potential impacts to human health and the environment if local conditions result in PV landfill disposal instead of recycling with consideration of the fermentation and methanogenic landfill phases and unlined landfills.

Methods

The DRAS model evaluates risk and hazard for several groundwater exposure scenarios (ingestion of groundwater, dermal absorption while bathing with groundwater, and inhalation of groundwater volatiles while showering) and for three surface exposure pathways (ingestion of surface water, ingestion of surface soil, ingestion of fish, and inhalation of vapor and particles).

Two types of DRAS model runs were conducted to investigate the relationship between landfill chemistry and potential emissions from landfilled PV modules, a model representing an acidic (fermentation) landfill phase, and a model representing a neutral to basic (methanogenic) landfill phase. The only difference between these model runs was the type of leachate data used, with acidic conditions using the results of TCLP testing (sodium acetate/acetic acid solvent) [8] and neutral to basic conditions using the results of column testing (deionized water solvent) [9]. The basic pH conditions from use of deionized water solvent are due to the release of sodium from the soda lime glass surface of the PV module sample. TCLP and column test parameters are summarized in Table 1. The TCLP test results were commissioned by First Solar and the column testing was performed by Norwegian Geotechnical Institute.

All other DRAS parameters were the same for the two model runs. For the waste management unit type, the “landfill” option was selected.

Table 1. Waste characterization test parameters for acidic and basic landfill conditions

		Acidic Landfill Conditions	Basic Landfill Conditions
Leachate Test		TCLP [8]	Column [9]
Fragment Size (cm)		1.0	0.4
pH	CdTe PV	2.88 for alkaline waste; 4.93 for neutral to acidic waste	8.0 - 10.3
	Si PV		8.1-9.8
Solvent		sodium acetate/ acetic acid	deionized water
Test Method		end-over-end agitation	water percolates through the sample
Test Duration		18 hr	3 weeks
Leachate Cd Concentration (mg/L)	CdTe PV	<1	<0.002
	Si PV	<0.1	0.007
	Limit[a]	1	0.3
Leachate Pb Concentration (mg/L)	CdTe PV	0.005	0.0025
	Si PV	3-11 (median <5)	0.008
	Limit[a]	5	3

[a]Regulatory limit for non-hazardous waste in the U.S. (TCLP) and EU (column test).
TCLP = Toxicity Characteristic Leachate Procedure.

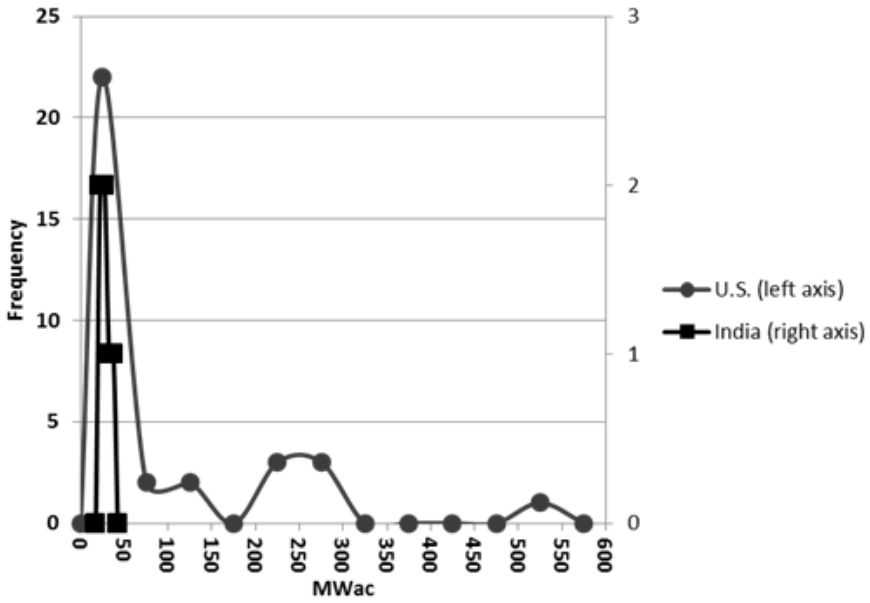

Figure 1. Utility-scale CdTe PV projects in developed and emerging markets.

Waste volume was set at 2,118 cubic yards, corresponding to a median size utility-scale PV project, 25 MWac [10] (Figure 1). For the waste management unit's active life, the "one year batch" option was selected as it is assumed that the entire 25 MWac project will decommissioned during one calendar year. In addition to the leachate concentrations for the acidic and basic scenarios provided in Table 1, the total constituent concentrations used were 383 mg Cd/kg and 15 mg Pb/kg for CdTe PV and 576 mg Pb/kg for Si PV [9].

Cd concentrations in soil and surface water are not explicitly provided in DRAS model output but they were derived from back-calculations using the DRAS-provided hazard quotients and media-specific hazard equations (equation 4-95 for surface water and equation 4-112 for soil in [2]). The modeled soil Cd concentration was compared to the lowest U.S. EPA Ecological Soil Screening Level for Cd [11]. Modeled surface water concentrations were compared to the U.S. EPA National Recommended Water Quality Criteria for Aquatic Life (Freshwater/Chronic) [12].

Exposure of ecological receptors to groundwater and ambient air were not evaluated in this assessment as it is standard ecological risk assessment practice to consider exposure via these pathways to be de minimis [2].

The methodology used to calculate hazards from the Pb concentrations that would result from landfilled Si and CdTe PV modules was different from the above-described methodology used for Cd. This is because toxicity factors (i.e., reference doses and cancer slope factors) are not available for Pb, as human health effects from Pb exposure may occur at blood lead levels so low as to be essentially without a threshold [13]. In this study, the potential for adverse effects to human health and the environment associated with Pb exposure were evaluated by comparing modeled media concentrations to medium-specific human health and ecological screening levels. This approach is consistent with DRAS guidance [2]. As with Cd, Pb concentrations for the relevant environmental media were not provided by DRAS and were derived as follows.

The concentration of Pb in groundwater was calculated using the DRAS-provided waste volume adjusted dilution attenuation factor (DAF) and by rearranging DRAS Equation 2-1 in [2] to solve for the waste constituent concentration in groundwater. Pb concentrations from the DRAS surface pathway (surface water, ambient air, and soil) were derived using a similar methodology which is based on the two DRAS input parameters that influence these media concentrations, waste volume and total constituent concentration in waste. The waste volume was held constant at 2118 yd^3 for all DRAS model runs. The total constituent concentrations in waste were 15 mg Pb/kg for CdTe PV and 576 mg Pb/kg for Si PV [9].

Once calculated, DRAS guidance recommends that the Pb concentrations are compared to the following human health-based levels: 0.015 mg/L for drinking water, 100 mg/kg for soil, and 0.2 $\mu g/m^3$ for ambient air [2]. DRAS sets the soil and air target levels at 25 percent of the actual risk-based levels based on the assumption that only 25 percent of the risk-based level is attributable to releases from the landfill modeled in DRAS. Ecological exposure to Pb was evaluated as described above for Cd, with comparison to Ecological Soil Screening Level for Pb [14], National Recommended Water Quality Criteria for surface water [12], and no ecological evaluation of groundwater or ambient air.

To experimentally evaluate the representativeness of the TCLP leachate data used with the DRAS model, five CdTe PV modules were crushed with a compactor at the top of a Municipal Solid Waste Landfill in the State of Arizona, USA. The modules were First Solar Series 3 Model 387 and were 0.6 m by 1.2 m in size, weighing approximately 12 kg. In the module design, the semiconductor layer was encapsulated between two sheets of protective glass, and a polymeric adhesive was used to laminate the two sheets of glass together.

The compactor used was a sheep's foot roller manufactured by Aljon, model 91K, with Caron cleats having a contact load of approximately 45,000 kg (Figure 2). The PV modules were placed on top of a 7 m × 12 m tarp consisting of a 1.5 mm thick linear low density polyethylene (LLDPE) liner. The compactor made six passes over the test installation. The

ground surface underlying the test installation consisted of loose soil which was firmer than the typical mixed waste conditions at the active face of a landfill. The residue from the crushed PV modules was collected and separately bagged for testing.

The procedure used to crush the PV modules may be considered a worst case for module loading as the landfill's compactor is one of the largest and heaviest compactors available on the market. Landfills outside the United States typically do not have compaction equipment, and if landfill compaction equipment is available, the equipment is typically a track mounted dozer rather than a compactor. A dozer is typically used when the landfill can only afford one piece of equipment because the dozer can push the waste as well as compact the waste once it has been pushed into the active face. A track mounted dozer would be lighter than the landfill's compactor and would therefore cause less damage to the PV modules.

Figure 2. Aljon model 91K compactor used to crush CdTe PV modules in a Municipal Solid Waste Landfill in the State of Arizona, USA.

After the PV modules were crushed, the resultant fragments were sized using gradation assessment methodologies. The crushed PV modules consisted of fragments that were not attached to the module as well as larger pieces that were held together by the interior lamination. The front glass was observed to be crushed more than the back glass. It appeared that the material fractures followed the stress pattern imparted by the compactor feet (Figure 3).

The gradation assessment adopted the particle count procedure of the U.S. Bureau of Reclamation known as a "Pebble Count" on a six inch by six inch section of crushed modules. The crushed fragments attached to the modules were counted with an assignment of maximum dimension of 13 mm, as most of the fragments were smaller than 13 mm minimum dimension. Some fragments were elongated and the dimensions in longer axis were in some cases much larger than a few inches. The residual fragments were subjected to the American

Society for Testing and Materials (ASTM) method specified in ASTM D 422 without hydrometer analysis.

After gradation testing was completed, a representative sample of the PV modules was selected from bag #2 (PV Module 2) and bag #5 (PV Module 5). This representative sample consisted of (by weight) approximately two thirds intact module (crushed but in one piece) and one third loose fragments. In both cases, the glass-laminate-glass bond of individual broken module fragments was maintained (i.e., individual module fragments remained laminated). PV Modules 2 and 5 were chosen on the basis of their location in the test installation (in the center and perimeter, respectively).

The samples were sent for waste characterization testing based on the TCLP waste characterization test used federally in the U.S. and the STLC test used in California. Once the samples were received by the laboratory they were analyzed without any further reduction in size. TCLP test parameters for the landfill fragments were the same as the standard TCLP test methods in Table 1 except for the particle size. STLC testing requires a longer test duration (48 hr) compared with TCLP (18 hr) and uses end-over-end agitation in a sodium citrate solution (pH 5).

Results

Based on fate and transport modeling with the U.S. EPA DRAS model, the one-time disposal of CdTe PV modules from a 25 MWac project to an unlined landfill is not likely to represent significant cancer risks or non-cancer hazards (Table 2).

The aggregate cancer risk for both the acidic and basic scenarios (4.49×10^{-9}) was well below the screening limit of 1×10^{-6}. Likewise, the aggregate non-cancer hazard indices for the acidic (4.55×10^{-2}) and the basic (1.21×10^{-3}) landfill stages were well below the screening limit of 1, with hazard quotients for the basic landfill condition an order of magnitude lower than under acidic conditions. Potential adverse impacts to ecological receptors are unlikely as modeled surface water and soil Cd concentrations were 2-4 orders of magnitude below their respective ecological criteria.

Similar to the results for Cd, modeled Pb concentrations indicate that the one-time disposal of either CdTe PV modules or Si PV modules from a utility-scale project (2,118 cubic yards of modules) to an unlined landfill is not likely to represent significant risks or hazards to human or ecological receptors (Table 3). Modeled media concentrations of Pb from Si PV modules were one to three orders of magnitude larger than those modeled from CdTe PV modules but all media concentrations were below human health and ecological criteria.

A key input to the DRAS model was the TCLP leachate concentration. Experimental crushing of CdTe PV modules in landfill conditions was conducted to evaluate the representativeness of the TCLP data used in the DRAS modeling. After crushing, the PV modules largely held together with separate broken pieces only occurring where impacted by one of the landfill compactor's feet, which created a punch-out in the module of the approximate size of the foot. The PV module material punched-out of the modules was recovered to the extent possible and consisted of the finer fraction of the overall sample (Figure 3).

Table 2. Human health and ecological screening assessment of Cd from landfill disposal of utility-scale CdTe PV modules

	Pathway	*Exposure Scenario*	*Receptor*	*Cancer Risk*		*Hazard Quotient*	
				Acidic Landfill Conditions	**Basic Landfill Conditions**	**Acidic Landfill Conditions**	**Basic Landfill Conditions**
Human Health	Surface Pathway[a]	Inhalation of particles	Adult Resident	4.49×10^{-9}	4.49×10^{-9}	---	---
		Ingestion of fish	Adult Resident	---	---	1.10×10^{-3}	1.10×10^{-3}
		Ingestion of drinking water	Adult Resident	---	---	1.17×10^{-6}	1.17×10^{-6}
		Ingestion of soil	Child to Adult Resident	---	---	1.85×10^{-5}	1.85×10^{-5}
	Ground-water Pathway	Ingestion of drinking water	Adult Resident	---	---	4.40×10^{-2}	8.54×10^{-5}
		Dermal absorption via bathing	Adult Resident	---	---	1.10×10^{-4}	2.13×10^{-7}
		Inhalation via showering	Adult Resident	---	---	---	---
		Dermal absorption via bathing	Child Resident	---	---	2.75×10^{-4}	5.34×10^{-7}
	Total			4.49×10^{-9}	4.49×10^{-9}	4.55×10^{-2}	1.21×10^{-3}
	Human Health Screening Limits			1×10^{-6}	1×10^{-6}	1	1
Ecological	*Media*	*Concentration Under Acidic Landfill Conditions*	*Concentration Under Basic Landfill Conditions*	*Ecological Criteria*[b]	*Units*		
	Surface Water	2.2×10^{-8}	2.2×10^{-8}	2.5×10^{-4}	mg/L		
	Ground-water	8.26×10^{-4}	1.65×10^{-6}	Not applicable	mg/L		
	Ambient Air	5.22×10^{-9}	5.22×10^{-9}	Not applicable	mg/m^3		
	Soil	7.23×10^{-4}	7.23×10^{-4}	3.6×10^{-1}	mg/kg		

[a]Cancer risk and hazard quotients are the same across acidic and basic landfill conditions in the surface pathway because they are a function of the same initial total waste concentration (383 mg Cd/kg).

[b]Ecological criteria for surface water from U.S. EPA National Recommended Water Quality Criteria for Aquatic Life (Freshwater/Chronic) [12] and for soil from U.S. EPA Ecological Soil Screening Level for Cd [11].

The results of the pebble counts and gradation tests were summarized in graphical form as fragment size distributions (Figure 4). On average, approximately one-quarter of module fragments were smaller than 1 cm, the fragment size used in TCLP testing, and approximately 1% of module fragments were smaller than 0.1 mm, the fragment size used in total availability testing (Table 4). Since waste characterization leaching tests exclusively use fragment sizes smaller than 1 cm, leachate potential derived from these tests represents a small fraction of the total volume of landfilled CdTe PV module waste, and is likely to result in an overestimate of leachate Cd concentration.

Table 3. Human health and ecological screening assessment of Pb from landfill disposal of utility-scale CdTe and Si PV modules

Module Type	Media Concentration	Human Health Criteria[a]	Ecological Criteria[b]
Groundwater (mg/L)			
CdTe PV	1.70×10^{-6}	1.50×10^{-2}	Not applicable
Si PV	1.73×10^{-3}	1.50×10^{-2}	Not applicable
Surface Water (mg/L)]			
CdTe PV	8.63×10^{-10}	1.50×10^{-2}	2.50×10^{-3}
Si PV	3.30×10^{-8}	1.50×10^{-2}	2.50×10^{-3}
Ambient Air (mg/m^3)			
CdTe PV	2.05×10^{-10}	2.00×10^{-4}	Not applicable
Si PV	7.86×10^{-9}	2.00×10^{-4}	Not applicable
Soil (mg/kg)			
CdTe PV	2.83×10^{-5}	1.00×10^{2}	1.10×10^{1}
Si PV	1.09×10^{-3}	1.00×10^{2}	1.10×10^{1}

[a]Human health criteria from U.S. EPA DRAS guidance [2].

[b]Ecological criteria for surface water from U.S. EPA National Recommended Water Quality Criteria for Aquatic Life (Freshwater/Chronic) [12] and for soil from U.S. EPA Ecological Soil Screening Level for Pb[14].

DRAS = Delisting Risk Assessment Software.

Table 4. Fragment size distribution of CdTe PV modules crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA

	Module #1	***Module #2***	***Module #3***	***Module #4***	***Module #5***	***Average (95% Confidence Interval)***
Proportion finer than 9.5 mm[a]	12%	27%	13%	40%	44%	27% (9-46%)
Proportion finer than 2 mm	1%	1%	0%	8%	10%	4% (0-10%)
Proportion finer than 4 mm	6%	6%	0%	19%	20%	10% (0-21%)
Proportion finer than 0.1 mm	0	1%	0%	2%	3%	1% (0-3%)

[a]9.5 mm, 2 mm, 4 mm, and 0.1 mm are waste characterization test method fragment sizes used for TCLP, STLC, Column, and Total Availability testing, respectively.

TCLP = Toxicity Characteristic Leachate Procedure.

STLC = Soluble Threshold Limit Concentration.

When sample variability is considered using 95% confidence intervals for mean fragment size, less than half of module fragments are smaller than 1 cm (Table 4) with 9-46% of fragments smaller than 9.5 mm and 0-3% smaller than 0.1 mm. These ranges again indicate that leaching potential is likely overestimated by waste characterization leaching tests which use fragment sizes smaller than 1 cm.

Figure 3. Compactor foot punch-out of a CdTe PV module crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA.

Table 5. Waste characterization test results for CdTe PV panels crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA[a]

	U.S. Regulatory Limit for Non-hazardous Waste (mg/L)	***CdTe PV Panel 2***	***CdTe PV Panel 5***	***CdTe PV Panel 2***	***CdTe PV Panel 5***
		TCLP (mg/L)	**TCLP (mg/L)**	**STLC (mg/L)**	**STLC (mg/L)**
Lead	5	<0.1	<0.1	<0.1	<0.1
Cadmium	1	0.19	<0.1	0.57	0.91

[a]Testing of landfill fragments conducted without further reduction in fragment size to compare with standard waste characterization testing in Table 1.

TCLP = Toxicity Characteristic Leachate Procedure.

STLC = Soluble Threshold Limit Concentration.

Consistent with the relatively large fragment sizes observed, laboratory analysis of the crushed modules yielded leachate concentrations within regulatory limits for non-hazardous waste based on the TCLP waste characterization test used federally in the U.S. and the STLC test used in California [15] (Table 5). Waste characterization testing of the landfill PV fragments was commissioned by First Solar and conducted without further reduction in fragment size to compare with standard waste characterization testing (1 cm fragment size in [8]). In both cases, leachate concentrations were within regulatory limits for non-hazardous waste.

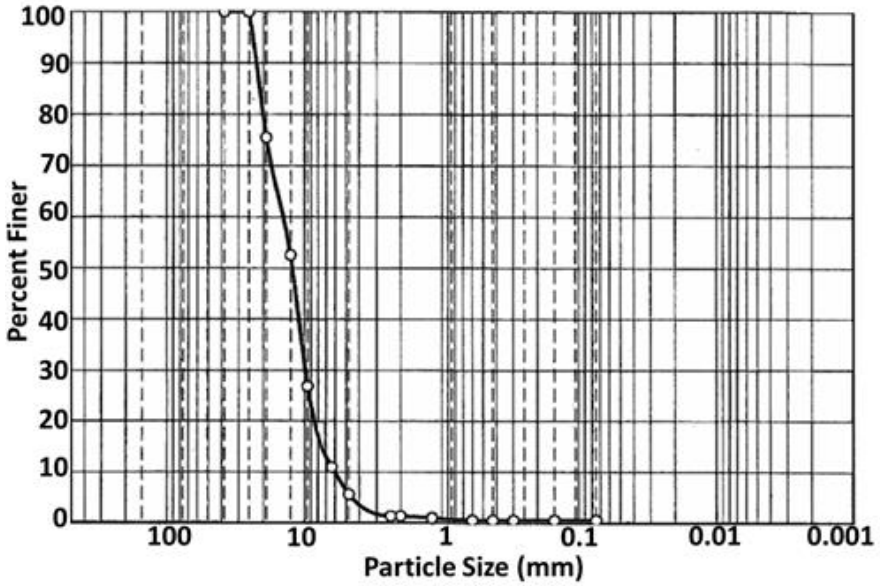

Figure 4. Fragment size distribution of CdTe PV module #2 crushed in a Municipal Solid Waste Landfill in the State of Arizona, USA.

Discussion

Previous life cycle assessment has found that emissions from CdTe PV systems are minimal in comparison with conventional electricity generation [16][17]. Previous assessments have assumed that end-of-life CdTe PV modules will be recycled. With on-site wastewater treatment and air emissions controls, emissions from CdTe PV module recycling are low, with Cd emissions to air and water of 5.89×10^{-9} and 8.92×10^{-8} kg per m^2 module, respectively [18]. Other potential end-of-life scenarios include incineration, disposal in a sanitary landfill, and disposal in a non-sanitary landfill. Incineration has not been considered here though has been evaluated by Raugei et al. [19]. With the use of engineering controls including daily cover, stormwater management, landfill liner, leachate collection, and groundwater monitoring, Cd emissions to soil (0.0001%) and to water (0.0026%) from electronics in sanitary landfills are low [20].

While recycling services and sanitary landfills are commonplace in industrialized regions such as the European Union and the United States, non-sanitary landfills are more prevalent in developing countries [21]. Therefore in this study, the third scenario (disposal in a non-sanitary landfill) has been evaluated with the U.S. EPA DRAS model. The results indicate that modeled Cd and Pb exposure from a one-time disposal of a utility-scale (25 MWac) PV project is not likely to cause adverse impacts to human health or the environment. The results presented here are generally consistent with Tvermoes et al. [6] which estimated low aggregate carcinogenic risks ($< 1\times10^{-6}$) and non-cancer hazard indices ranging from low (0.03) to slightly greater than the screening limit (1.77). The upper-bound non-cancer hazard index in Tvermoes et al. [6] resulted from a scenario that included landfilling of an 80 MWac project followed by continuous disposal of CdTe modules over the active life of the landfill

(20 years) totaling an additional 350 MWac. In contrast, this study modeled the one-time disposal of waste volume equivalent to a 25 MWac project which is a median size for a utility-scale PV project (Figure 1). While comparison of the two investigations indicates that large waste volumes and multiple disposal events can increase potential impacts from landfilled PV module waste, there is a margin of safety of 20-800 for the aggregate hazard index, 220 for the aggregate cancer risk, and 500-11,000 for ecological impacts relative to screening limits in the 25 MWacCdTe PV project evaluated in this study (Table 2). For Si PV, the margins of safety for human health impacts are a factor of 8 for impacts to groundwater and 25,000-450,000 for impacts to surface water, ambient air, and soil. In addition for Si PV, the margins of safety are 10,000-75,000 for ecological criteria (Table 3).

Another difference between this investigation and Tvermoes et al. [6] is the accounting for potential changes in the mobility of metals over the life of a landfill. Landfills move through two main phases during their lifetime with an initial anaerobic fermentation phase (acidic pH) lasting from weeks to months followed by a longer anaerobic methanogenesis phase (neutral to slightly basic pH) that can last for decades to centuries [7].

The adsorption/retention of Cd onto soils is strongly pH-dependent. During the methanogenic phase, metal ions are immobilized by the formation of metal sulfides as a result of reducing conditions. When the pH is below 6-7, cadmium is desorbed from these materials. This mechanism was tested in this investigation by using the results of different types of leachate tests as inputs for the groundwater pathway (Table 1). The aggregate hazard index under basic conditions (~0.001) was an order of magnitude lower than under acidic conditions (~0.05) (Table 2), indicating that the default DRAS assumption of acidic landfill conditions over the lifetime of the landfill can considerably overestimate potential impacts.

However, it should be noted that Kjeldsen et al. [7] postulate that after long-time periods (e.g., hundreds or even thousands of years) air may gradually intrude into the landfills, creating aerobic conditions, organic matter oxidation, increasing CO_2 concentrations and lowering of pH.Aucott [4] reported laboratory experiments where Cd previously bound as a sulfide precipitate was released to the aqueous phase where conditions were changed from slightly anaerobic to aerobic. However, Cd was subsequently removed from solution either by adsorption on iron hydroxides or by precipitation in the form of carbonates.

In addition, this investigation uses a screening level assumption that the toxicity of CdTe is equal to that of cadmium chloride and/or elemental cadmium. Based on recent toxicity testing, this assumption likely overestimates CdTe toxicity by approximately two orders of magnitude [22]. The modeling presented here also assumes that PV modules are the only source of constituents of concern in the modeled landfill and is therefore only considering incremental risk from PV disposal.

Another screening level assumption used in this analysis is related to leaching potential and fragment size. Leaching potential increases with increased surface area that results from smaller fragment size, and waste characterization tests use relatively small fragment sizes (0.1 mm to 1 cm). These fragment sizes are considerably smaller than those that would be routinely generated by typical waste handling practices related to disposal in a landfill, with on average approximately three-quarters of module fragments larger than 1 cm and approximately 99% of module fragments larger than 0.1 mm (Table 4).

Precipitation is a factor that is related to the risks associated with the disposal of PV modules in unlined landfills. Precipitation is required to produce landfill leachate and there is generally an inverse relationship between the high solar irradiation that is common to utility-

scale PV project locations and the amount of annual precipitation. Many existing and planned utility-scale PV projects are located in regions that receive low amounts of precipitation [23] and therefore landfill disposal in these areas may not produce significant quantities of leachate. For example, in South Africa, landfills located in arid and semi-arid areas do not have leachate collection requirements, as water balance calculations indicate that it is unlikely that significant leachate will be generated [24].

Use of environmentally sensitive materials such as Pb, Se, Cr, and Cd compounds are commonplace in the PV industry. In addition to evaluating potential Cd emissions, this study compares DRAS-modeled Pb concentrations from landfilled utility-scale Si and CdTe PV modules, indicating no exceedances of media-specific human health or ecological screening levels (Table 3). Estimated media concentrations of Pb from Si PV in ground water, surface water, ambient air, and soil are comparable to concentrations of Cd from CdTe PV (Tables 2,3), indicating that responsible disposal is necessary for all PV technologies.

With respect to both environmental impacts and resource efficiency, the most sustainable way to manage end-of-life PV modules is recycling. The PV recycling industry is expected to scale significantly over the next 10-15 years as annual waste generated by end-of-life PV modules is predicted to increase to over 1 million tons by 2035 [25].

The recycling industry will generate jobs and recover valuable materials. For example, CdTe PV recycling technology (Figure 5) has been in commercial operation since 2005 and has already recycled over 1.5 million modules with yields of approximately 90% and 95% for glass and semiconductor recovery, respectively. End-of-life collection and recycling, including semiconductor refining, accounts for only approximately 10% of the total life cycle energy payback time of CdTe PV [18] and can result in net reductions in life cycle primary energy demand when recycling products are accounted for as credits [26].

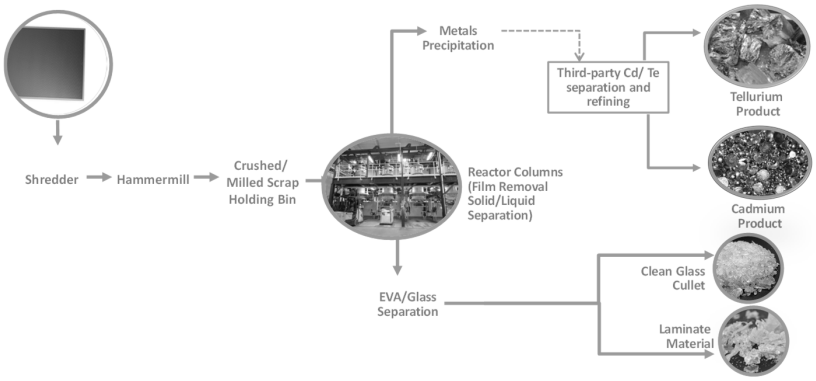

Figure 5. Schematic of CdTe PV module recycling process with 95% and 90% yields of semiconductor material and glass, respectively.

An understanding of future PV recycling can be gained by examining trends in electronic waste regulation. The EU has mandated the recycling of waste electrical and electronic equipment since 2003, and end-of-life collection and recycling of PV modules has recently been included within the scope of the recast WEEE Directive [1]. Whereas the text of the Directive depicts a mass-based recovery quota which could be obtained by recycling of PV module glass and aluminum frames only, the European Commission also clearly saw the need

to develop high value recycling standards (which can include recycling of PV semiconductor material) and mandated the European Standardization Organization CENELEC to develop these standards [27]. High value recycling is necessary for maximizing resource recovery and diverting metals from disposal.

Conclusion

While recycling services and sanitary landfills are commonplace in industrialized regions such as the European Union and the United States, non-sanitary landfills are more prevalent in developing countries. With respect to the latter, based on fate and transport modeling with the U.S. EPA DRAS model, disposal of utility-scale CdTe PV modules in unlined landfills is unlikely to result in adverse health or environmental impacts. The leaching potential assumed in the fate and transport model is based on waste fragment sizes that are considerably smaller than those that would be routinely generated by typical waste handling practices in a landfill, providing an additional margin of safety. Potential impacts may be further limited by use of sanitary landfills and high value recycling, with the latter providing the important benefit of resource recovery.

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References

[1] European Parliament and the Council of the European Union. *Official Journal of the European Union*.2012. 24.7.2012, L 197, 38-71.

[2] U.S. Environmental Protection Agency. *RCRA Delisting Technical Support Document*; Land and Chemicals Division, Region 5: Chicago, IL, 2008.

[3] U.S. Environmental Protection Agency. (2009). *Technical Factsheet on Cadmium*. http://www.epa.gov/safewater/pdfs/factsheets/ioc/tech/cadmium.pdf

[4] Aucott, M. 2006. *The fate of heavy metals in landfills: A Review*, The New York Academy of Sciences, New York, NY.

[5] Fthenakis, V. M. *Renewable and Sustainable Energy Reviews*. 2004, 8, 303-334.

[6] Tvermoes, B.; de Sylor, M. A.; Sahmel, J.; Cyrs, W.; Paustenbach, D. 2011. *Proc. Society of Toxicology Annual Meeting*; Washington, D.C., 2011, Abstract 2909.

[7] Kjeldsen, P.; Barlaz, M.A.; Rooker, A. P.; Baun, A.; Ledin, A.; Christensen, T.H. *Critical Reviews in Environmental Science and Technology*. 2002, 32(4), 297-336.

[8] Bousselaire, J. 2013. *Analytical Report*, Test America, Irvine, CA.

[9] Arp, H. P. *Leaching from mc-Si PV module material – results from batch, column and availability tests. Comparison with thin film CdTe PV modules*; Norwegian Geotechnical Institute: Oslo, Norway, 2010.

[10] First Solar. (2012). *Projects*. http://www.firstsolar.com/en/ Projects#namerica

[11] U.S. Environmental Protection Agency. *Ecological Soil Screening Levels for Cadmium. Interim Final*; Office of Solid Waste and Emergency Response: Washington, D.C., 2005.
[12] U.S. Environmental Protection Agency. (2013). *National Recommended Water Quality Criteria. Aquatic Life Criteria Table*. http://water.epa.gov/scitech/swguidance/ standards/ criteria/current/index.cfm#altable
[13] U.S. Environmental Protection Agency. (2004). *Lead and compounds (inorganic) (CASRN 7439-92-1)*. http://www.epa.gov/iris/ subst/0277.htm#woe
[14] U.S. Environmental Protection Agency. *Ecological Soil Screening Levels for Lead, Interim Final*; Office of Solid Waste and Emergency Response: Washington, D.C., 2005.
[15] McCutcheon, C. *Analytical Report*; TestAmerica: Phoenix, AZ, 2013.
[16] Fthenakis, V.M.; Kim, H.C.; Alsema, E. *Environmental Science and Technology*. 2008, 42(6), 2168-2174.
[17] Held, M.; Ilg, R. *Progress in Photovoltaics; Research and Applications*. 2011, 19, 614-626.
[18] Sinha, P., Cossette, M.; Ménard, J.-F. *Proc. 27th EU PVSEC*; Frankfurt, Germany, 2012, 4653 – 4656.
[19] Raugei, M.; Isasa, M.; Palmer, P.F. *International Journal of Life Cycle Assessment*. 2012, 17, 192-198.
[20] European Commission. *Commission staff working paper accompanying the Proposal for a Directive of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE) (recast) Impact Assessment. Annex 5*; Commission of the European Communities: Brussels, Belgium, 2008.
[21] Hoornweg, D.; Bhada-Tata, P. *What a Waste: A Global Review of Solid Waste Management*; World Bank: Washington, D.C., 2012.
[22] Kaczmar, S. 2011. *Proc. SETAC North America 32nd Annual Meeting*; Boston, MA, 2011, 226.
[23] Komoto, K.; Breyer, C.; Cunow, E.; Megherbi, K.; Faiman, D.; van der Vleuten, P. *Energy from the Desert: Very Large Scale Photovoltaic Power – State of the Art and into the Future*; Routledge: New York, NY, 2013.
[24] Johannessen L.M; Boyer, G. *Observations of Solid Waste Landfills in Developing Countries: Africa, Asia, and Latin America*; World Bank: Washington, D.C., 1999.
[25] GlobalData. *Solar Module Recycling - A Necessary Step to Maximize Environmental Benefits of Solar PV Industry*; GlobalData Research: New York, NY, 2012.
[26] Held, M. *Proc. 24th EU PVSEC*; Hamburg, Germany, 2009, 2370-2375.
[27] European Commission. *Mandate to the European Standardisation Organisations for Standardisation in the Field of Waste Electrical and Electronic Equipment (Directive 2012/19/EU (WEEE))*; Directorate – General Environment: Brussels, Belgium, 2013.

Reviewed by Vasilis Fthenakis, Columbia University and Brookhaven National Laboratory.