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Landfill waste and recycling: Use of a screening-level risk assessment tool for end-of-life cadmium telluride (CdTe) thin-film photovoltaic (PV) panels

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HIGHLIGHTS

- Analysis of possible human health risk posed by disposal of CdTe panels into landfills.
- Qualitative comparison of risks associated with landfill disposal and recycling of CdTe panels.
- Landfill disposal of CdTe panels does not pose a human health hazard at current production volumes.
- There could be potential risks associated with recycling if not properly managed.
- Factors other than concerns over toxic substances will likely drive the decisions of how to manage end-of-life PV panels.

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ABSTRACT

Grid-connected solar photovoltaic (PV) power is currently one of the fastest growing power-generation technologies in the world. While PV technologies provide the environmental benefit of zero emissions during use, the use of heavy metals in thin-film PV cells raises important health and environmental concerns regarding the end-of-life disposal of PV panels. To date, there is no published quantitative assessment of the potential human health risk due to cadmium leaching from cadmium telluride (CdTe) PV panels disposed in a landfill. Thus, we used a screening-level risk assessment tool to estimate possible human health risk associated with disposal of CdTe panels into landfills. In addition, we conducted a literature review of potential cadmium release from the recycling process in order to contrast the potential health risks from PV panel disposal in landfills to those from PV panel recycling. Based on the results of our literature review, a meaningful risk comparison cannot be performed at this time. Based on the human health risk estimates generated for PV panel disposal, our assessment indicated that landfill disposal of CdTe panels does not pose a human health hazard at current production volumes, although our results pointed to the importance of CdTe PV panel end-of-life management.

1. Introduction

The photovoltaic (PV) industry is currently one of the fastest growing industries worldwide because of decreases in the cost of PV modules, as well as concerns over the limited supply of fossil fuels and greenhouse gas emissions (Bosi and Pelosi, 2007; EPIA (European Photovoltaic Industry Association), 2013; SEIA (Solar Energy Industries Association), 2013). In 2012, the installed PV capacity of the United States (U.S.) grew 76% from the previous year, and continued growth is expected to occur both in the U.S. and worldwide (EPIA (European Photovoltaic Industry Association), 2013; SEIA (Solar Energy Industries Association), 2013). Crystalline silicon has traditionally dominated the PV panel production market. However, the increasing energy conversion efficiencies and decreasing costs of thin film PV technologies [e.g., cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous silicon], which employ thinner layers and a greater variety of materials forming the energy-producing semiconductor layer, have allowed these panels to rapidly expand their market share over the past decade (Chopra et al., 2004; Mulvaney et al., 2009; SEIA (Solar Energy Industries Association), 2011; U.S. DOE (U.S. Department of Energy), 2010; Ullal and Von

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Roedern, 2007). CdTe has had the most success out of all the metal-based thin film technologies because of a combination of low manufacturing costs and relatively high energy conversion efficiencies (Mulvaney et al., 2009; Ullal and Von Roedern, 2007). In fact, annual power production for CdTe panels grew 181% between 2004 and 2009, far exceeding the growth rate of other thin film technologies (Zweibel, 2010). As a result, we focused our analysis on this type of thin film PV panel.

While CdTe PV power generation has the environmental benefit of zero emissions during operation, the use of potentially toxic metals in the PV panels themselves has spurred questions about the potential adverse human health and environmental impacts of this technology. Several researchers have expressed concerns regarding the potential risks to human health or the environment associated with disposing large quantities of CdTe panels in a single landfill over an extended period of time (SVTC (Silicon Valley Toxics Coalition), 2011; Fthenakis, 2004; Mulvaney et al., 2009; Raugei and Fthenakis, 2010).

The U.S. Environmental Protection Agency (EPA) regulates end-of-life disposal of solar products and other waste under the Federal Resource Conservation and Recovery Act (RCRA). To be characterized as hazardous waste, PV panels must fail the Toxicity Characteristics Leaching Procedure (TCLP) (EPA (Environmental Protection Agency), 2004). In this procedure, a minimum 100 g of waste is reduced to a primary particle size of <9.5 mm in diameter and soaked in 20 times its weight of extraction fluid, of a specified pH, for approximately 18 h. Then, the liquid extract is filtered from the solid waste and the chemicals of concern are analyzed by mass spectrometry or atomic absorption (EPA (Environmental Protection Agency), 1992, 1994, 2004). The U.S. EPA generally sets TCLP concentration limits for a chemical by applying a dilution/attenuation factor of 100 to the maximum contaminant level (MCL) for drinking water. This dilution factor is used to account for the concentration reduction expected to occur between the point of leachate generation and the point of human or environmental exposure (EPA (Environmental Protection Agency), 1994, 2009b).

TCLP tests performed on CdTe panels have shown measurable leachate concentrations of a number of metals of concern, including selenium, lead, and cadmium. Among these metals, cadmium is of most concern because some studies have reported cadmium TCLP concentrations that exceeded its TCLP limit of 1.0 mg/L (Table 1) (Cunningham, 1999; Eberspacher, 1999; EHSO (Environmental Health & Safety Online), 2008; Goozner, 1999; Goozner et al., 1997; Moskowitz and Fthenakis, 1991; NGI (Norwegian Geotechnical Institute), 2010; Patterson et al., 1994). Thus, we chose to focus on cadmium risk.

Cadmium exposure has been associated with various adverse health endpoints including obstructive lung disease, osteoporosis, kidney dysfunction, hypertension, and neural effects, depending on the dose and route of exposure (ATSDR (Agency for Toxic Substances and Disease Registry), 2008; IARC (International Agency for Research on Cancer), 1993; Il'yasova and Schwartz, 2005; Jarup et al., 1998; Kazantzis, 2004; Kriegel et al., 2006; Schwartz and Reis, 2000; Waalkes, 2003). In addition, the carcinogenic potential of cadmium has been classified by several different agencies. The U.S. Environmental Protection Agency (EPA), the International Agency for Research on Cancer (IARC), and the American Conference of Governmental Industrial Hygienists (ACGIH) have classified cadmium as a Group B1 (probable), Type 1 (known), and A2 (suspected) human carcinogen, respectively (ACGIH (American Conference of Industrial Hygienists), 2001; EPA (Environmental Protection Agency), 1987; IARC (International Agency for Research on Cancer), 1993).

While life cycle analyses have been published that evaluate cadmium emissions during the production and use of CdTe PV panels, none to our knowledge have quantified the potential health risks posed by the disposal of used panels into landfills (Baumann et al., 1995; Fthenakis, 2004; Fthenakis and Kim, 2011; Sinha et al., 2008). The primary objective of our study, then, was to evaluate the potential human health risk from cadmium emission associated with CdTe PV panel disposal. The distribution and fate of cadmium in the environment following CdTe panel disposal into a landfill was modeled using the Delisting Risk Assessment Software (DRAS), a conservative screening-level risk assessment tool developed by the U.S. EPA for the purpose of computing human health risks associated with exposure to chemicals through groundwater and surface pathways (EPA (Environmental Protection Agency), 2008b). As a screening-level technique, our analysis sought to identify a volume of CdTe panel waste deposited into a single landfill that would warrant a full-scale risk assessment. We also evaluated whether such a volume of waste could feasibly be disposed in a single landfill.

An alternative end-of-life scenario for CdTe PV panels is recycling, and various authors have presented this option as a safer or more responsible way to manage end-of-life PV panels (Fthenakis, 2004; McDonald and Pearce, 2010; Mulvaney et al., 2009). A secondary objective of this study was therefore to compare the potential risk associated with CdTe PV panel landfill disposal to potential risk associated with recycling. Toward this end, we performed a literature search to identify studies regarding cadmium emissions and potential human health risks that may be associated with CdTe panel recycling. The findings from this literature search were summarized and compared to the results from our screening-level risk assessment for landfill disposal. It should be noted that although PV panels could also be incinerated after their useful life, we limited our analysis to the landfill disposal and recycling scenarios.

Table 1
TCLP test results from literature.

References	TCLP concentrations (mg/L)		
	Cadmium	**Lead**	**Selenium**
Cunningham (1999)	0.1–0.45	ND	ND
Eberspacher (1999)	0.7–9.5	0.04–0.4	ND
Goozner et al., 1997	0.915	0.038	ND
Goozner (1999)	0.01–0.92	0.04–0.11	0.20–0.26
Moskowitz and Fthenakis (1991)	8–9.5	0.13–0.26	0.1*
Patterson et al. (1994)	0.61	ND	ND
NGI (Norwegian Geotechnical Institute) (2010)	0.73	0.02	0.01
TCLP limits	1.0	5.0	1.0

ND = no data.

* Value reported was likely the limit of detection.

2. Materials and methods

The Delisting Risk Assessment Software (DRAS) was used to perform a screening-level risk assessment evaluating non-carcinogenic and carcinogenic risks associated with cadmium exposure from CdTe PV panel disposal in landfills. We selected the DRAS software tool because it is applicable to the U.S., was developed by the U.S. EPA (Region 6), and encompasses an appropriate variety of exposure pathways and routes for a screening-level risk assessment. The DRAS software draws from a number of models to address various aspects of contaminant fate and transport, including the U.S. EPA Composite Model for Leachate Migration with Transformation Products (CMTP), the Universal Soil Loss Equation (USLE), and the Ambient Air Dispersion Model (AADM). To our knowledge, no other comparable software