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Sustainability evaluation of CdTe PV: An update

Vasilis Fthenakis [*], Clement Athias, Alyssa Blumenthal, Aylin Kulur, Julia Magliozzo, David Ng

Center for Life Cycle Analysis, Earth and Environmental Engineering, Columbia University, New York, NY, USA

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ABSTRACT

Cadmium Telluride thin-film photovoltaics (CdTe PV) have succeeded in producing electricity at grid-parity costs in sunny regions, with particular application in large solar facilities, totaling 25 GW since the start of commercial production in 2002. A rigorous sustainability evaluation is appropriate, in view of this drastic growth in CdTe PV production and deployment. This paper provides an update of a 2004 article by the leading author, on the life cycle impact of cadmium in CdTe PV and expands it to resource recovery and up-normal events. Thus, we analyze the environmental sustainability of CdTe PV in manufacturing, product use, and end-of-life management, and critically review recent studies on CdTe risks associated with large PV power plants, with special focus on potential failures during extreme events. We substantiate that module manufacturing by the current leader in commercial CdTe PV production, does not pose sustainability concerns because their Cd management program is extensive and sufficiently protects workers from Cd exposure, as evidenced by worker biomonitoring data. During product use, we identified and evaluated impacts during fires and extreme weather conditions, based on experimental data, worst-case modeling, and historical events. Based on credible data and corollary evidence we determined that there are not environmental impacts during normal conditions and that environmental impact risks are minimal during conceivable extreme conditions. Regarding end-of-life management of CdTe PV, recycling is the preferred management option for minimizing potential environmental impacts in comparison to landfill disposal or incineration, while providing semiconductor materials for future CdTe PV manufacturing.

1. Introduction

Fthenakis et al., *2008,* predicted that by 2030 solar could provide 252 GW of power in the US alone [1]. Their *Solar Grand Plan* laid out an approach to generating 69% of US electricity and 35% of total energy using solar power by 2050. The US Department of Energy Solar Energy Technologies Office (SETO) projects utility scale solar photovoltaic capacity will grow by 127 GW and that 64% of electricity will be generated by renewables in 2050 [2]. These predictions are being materializing. The price of photovoltaics (PV) has been consistently falling over time, with the electricity price as of 2018 well below \$0.06/kWh at utility scale. This drop was achieved faster than expected; SETO had predicted this price to be reached in 2020. If the trend continues as described in their *SunShot* report, \$0.03/kWh can be reached by or before 2030 [3]. This would make the cost of electricity from solar power lower than that generated by most fossil fuel sources.

These expeditious developments necessitate a fresh look at the viability of solar technologies; this paper examines the sustainability of a large growth of cadmium telluride photovoltaic (CdTe PV), which is exemplified as the lowest manufacturing cost technology in the *Solar Grand Plan.* Its advantages, in addition to low cost, are a close to optimal direct bandgap of 1.45 eV, high optical absorption coefficient, and easy processing [4]. Currently, CdTe thin films make up under 10% of the world PV market, with production capacity expected to grow [5]. Most commercial CdTe cells are produced by First Solar who has achieved cell record efficiencies of 22.1% and average commercial module efficiencies of 17.5–18% [6]. CdTe PV's R&D and production history starts several decades after the early work by Bell Labs in the 1950's on crystalline-Si PV. The following companies worked on commercializing the technology: Matsushita, BP Solar, Solar Cells Inc. (the predecessor to First Solar), Abound Solar, and GE PrimeStar. Currently, the leading thin-film CdTe PV manufacturer is First Solar, which since 2002 has produced 25 GW of PV modules.

Fthenakis, Kim and Alsema, 2008, conducted a comparative life-cycle-assessment (LCA) comparing crystalline Si, and thin-film PV technologies based on life-cycle-inventory (LCI) data from thirteen PV manufacturers [15]. The showed that among all commercial of PV technologies, thin-film cadmium telluride (CdTe) PV emits the least

* Corresponding author.
E-mail address: vmf5@columbia.edu (V. Fthenakis).

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amount of harmful air emissions as it requires the least amount of energy during the module production. More recent LCA articles [83–91] comparing PV technologies across multiple indicators (e.g., cumulative energy demand, global warming potential, acidification potential, ozone depletion, particulate matter, human toxicity, ozone depletion, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, terrestrial acidification, marine acidification, land occupation, and resource use), also showed that CdTe PV is advantageous across all environmental impact categories, to currently commercial PV technologies.

When evaluating sustainability, it is important to, in addition to LCA studies of normal life-cycles, to take a holistic approach in a comparative framework. With respect to applying sustainability frameworks to photovoltaics, the main metrics are affordability, resource availability and minimum environment impact (Fig. 1) [7]. The objective of this paper is to update the earlier review with data reflecting research and deployment over the past 15 years in order to compare precautionary concerns about the technology with actual performance, given that 25 GW of CdTe PV modules have been deployed globally [8]. Thus, we discuss resource availability and the environmental and health impacts of the use of cadmium compounds in the manufacturing, product use, and end-of-life steps of the life cycle of CdTe PV. The life cycle of Cd in CdTe PV was documented in a 2004 review just after the technology was initially commercialized [9]. This paper provides an update of the 2004 article on the life cycle impact of cadmium in CdTe PV and expands it to resource availability and potential environmental impacts during up-normal events. We have chosen to exclude economic factors from the scope of this paper because PV costs have almost reached grid parity, coupled with the fact that CdTe thin films have been among the lowest production cost PV technologies [10].

2. Raw Materials

2.1. Cadmium (Cd)

Cadmium is a group 12 metal mainly mined as a by-product of zinc (~80%) and lead ores (~20%) [9]. Zinc ores contain approximately 3–11% zinc and 220 ppm cadmium [11]. Due to cadmium being a waste product of the Zn production, its emissions do not count towards the life-cycle analysis of CdTe but rather of zinc products. If an increase in the production of CdTe thin films would increase the mining of cadmium, these emissions would have to be counted and would thus increase the energy payback time. This does not appear to be a concern in the near future as a problem of oversupply is predicted by Matsuno et al. [12] and Cha et al. [13]. It can also be argued that encapsulating cadmium as CdTe in PV modules is an important alternative to its current uses and would actually reduce cadmium waste [14]. Historical health effects from Cd exposure such as "itai-itai disease" in Japan was caused by Cd in Zn mining waste that was discharged into the environment as opposed to being used in products. Currently, the major source of Cd emissions to air is coal combustion. Although coal-burning power plants in the US and elsewhere are equipped with electrostatic precipitators (ESP) that remove about 98% of Cd from combustion exhaust streams, the amount that escapes controls account to about 4 g per GWh. The whole life cycle of CdTe may emit 0.2 g/GWh so CdTe PV would prevent ~4g of Cd in air emissions when used instead of the UCTE electricity grid in Continental Europe [15].

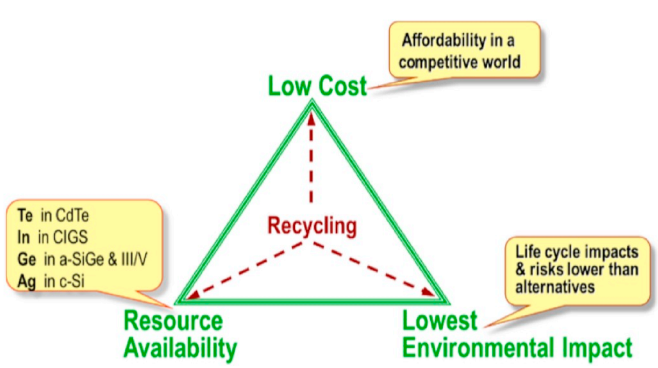

Fig. 1. The three pillars of sustainable PV growth.

The main pathways of Cd emissions and exposure are [16]:

1) *Agricultural soils and food*: Atmospheric deposition from coal-burning power plants (but also, in a large part, the use of phosphate fertilizers) causes the content of Cd in agricultural top soil to increase, which over time would be reflected in an increased human ingestion of Cd. The major chronic route of exposure to Cd for the non-smoking general population is via food, and smokers have increased exposure to Cd through soil Cd accumulation in the tobacco plant.
2) *Aquatic environment*: In the aquatic environment, levels of Cd may exceed background levels because of atmospheric deposition, domestic wastewater, and industrial discharges.
3) *Disposal and landfills*: Cd can enter landfills through disposal of spent cadmium-containing products, non-cadmium containing products which may contain cadmium impurities, and naturally-occurring wastes such as grass, food and soil which inherently contain trace levels of cadmium.

The refinery production of Cd in 2017 was 23,000 metric tons with most of this (~85%) being used for NiCd batteries and only about 0.06% being used for PV production [14]. Since CdTe solar cells are a very small percent of global Cd use, the Cd demand for CdTe solar cells can easily be met given the decline of other uses [12,13]. The direct Cd emission from mining, smelting, purification and synthesis are 0.015 g/GWh; this was calculated with the assumption of a module lifetime of 30 years, 9% module efficiency and an average insolation of 1800 kWh/m^2/yr [15], and would be about half as much given current module efficiency of 17–18%. The Cd emitted in the life cycle of CdTe cells is orders of magnitude below that of coal plants, which can be anywhere from 90 to 300 times higher [17].

2.2. Tellurium (Te)

Tellurium is a by-product of copper mining. A potentially limiting factor for CdTe PV production is Te availability. Te supply is dynamic, as a combination of improvements in the PV module tellurium intensity, tellurium recovery from Cu ores, and recycling. A combination of primary and secondary production (Fig. 2) would enable an annual production of CdTe PV on the order of 100 GW/yr by mid-century at reasonable cost [18], which would result in TW-scale deployment on the

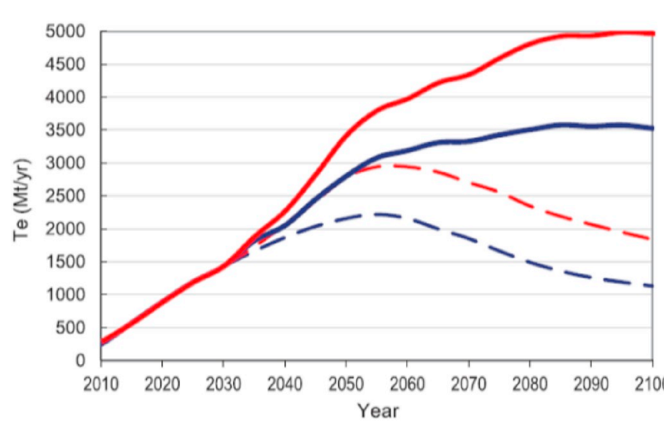

Fig. 2. Projections of Te primary(dotted line) and total (primary and secondary from recycling (solid line) production (MT/yr).

order of a decade (Fig. 3). It is worth noting that of the 11 Gg of refined Te that has been produced between 1940 and 2010, it is estimated to only be 4.5% of Te mined, indicating that there is order of magnitude room for improving Te recovery [19].

Currently the PV sector accounts for 26% of global Te consumption [20]. Due to tellurium supply being proportional to copper production, this represents a supply risk as its supply depends on that of the "parent" metal and a concentration risk as the supply is controlled by a small number of countries and companies. The production from copper and, thus, Te is growing at a rate of 1–2% a year and is estimated to peak mid-century [21,23].

Ways to overcome the scarcity problem include refining Te from primary metals currently not being used (for example, Pb), mining Cu ores high in Te content, and critically, improving the recovery of Te from Cu anode slimes [22]. The recovery from slimes is currently at ~40% and is estimated to be able to increase to ~80% with current technologies [23,24]. It is claimed that on the laboratory scale using acid pressure leaching processes, more than 90% of Te can be removed from Cu anode slimes [25,26]. Te production could also be increased by mining it directly from bismuth telluride ores (Mexico, China and Sweden) with Te concentrations of ~20% [21]. However, if direct mining is used as a Te source, the environmental burden in the life cycle assessment will increase [27]. Other ways to increase Te supply include: decreasing the thickness of the CdTe layer, increasing the device efficiency, and using material from recycling [28]. Demand side management strategies have led to 50% reductions in the semiconductor intensity of CdTe PV modules since 2009, and additional reductions are expected with further increases in material utilization and module and system efficiencies [29].

3. Cadmium telluride toxicology

Due to initial limited toxicological data on this compound, it has long been assumed that CdTe properties were close to those of Cd, despite the strong chemical bond between Cd and Te (>5 eV) that distinguishes the compound CdTe from the element Cd [30]. This "read-across approach" is carefully investigated by Kaczmar [31]. Synthesizing previous studies on CdTe from a dossier of toxicological properties shown in Table 1 (e.g., solubility, bioaccessibility, acute toxicity, repeated dose toxicity, reproductive toxicity, acute aquatic toxicity, terrestrial ecotoxicity) developed by the European Chemical Agency (ECHA) for EU REACH registration [34], Kaczmar 2011 [92] showed that CdTe has lower toxicity than cadmium. Also, Sinha et al. [93] reported, based on the EPA USEtox database, that freshwater ecotoxicity characterization factors (CF) of CdTe are in a low range compared to metal ions in the database, due primarily to lower ecotoxicity effects on freshwater ecosystems measured for three trophic levels (algae, crustaceans, fish).

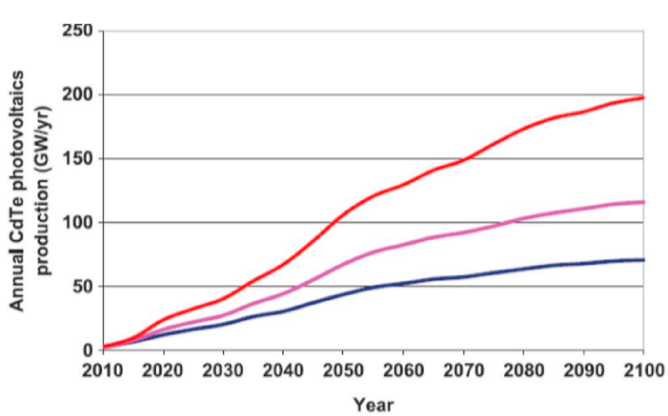

Fig. 3. Projections of CdTe PV growth potential (GW/yr) based on Te availability for optimistic, The red, pink, and blue curves correspond to the optimistic, most likely, and conservative scenarios[24]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Potential ecotoxicity impacts of CdTe were estimated to be approximately 3 orders of magnitude lower than that of Cd [92]. CdTe is also less bioavailable than Cd [32], partly because it is less soluble (solubility product K_{sp} of 9.5×10^{-35} for CdTe compared to 2.3 for Cd at 25 °C, pH = 7) [33]. In the case of acute and repeated dose inhalation testing, respirable CdTe particle sizes (1–4 μm diameter) were utilized, whereas the CdTe powder utilized in PV manufacturing is not respirable (volume mean diameter of 155.67 μm).

4. Manufacturing

Cadmium telluride photovoltaic cells are typically manufactured through a high-rate vapor transport deposition (VTD) process [36]. A low-cost soda lime glass is the superstrate upon which the module is built. It has a tin oxide coating, which serves as the transparent conductive contact. The semiconductor layers are applied upon this contact through VTD. Each layer is laser scribed to form the electrical channels in the module. $CdCl_2$ is diffused into the polycrystalline matrix to improve the electronic properties of the module. The back contact is then applied by sputtering. A final laser scribing completes the circuit channels and separates individual cells within the module. The module is then laminated with a polymeric adhesive and another layer of glass along with edge sealant, before being thermally sealed for final encapsulation. The module is tested under light for performance before being packed for shipment [37–39].

CdTe is sublimed in the VTD process, and the fraction that is not deposited is exhausted the form of fine particulates. HEPA filtration systems (with a 99.97% capture efficiency for 0.1 μm particles) are used to control emissions to well below regulatory standards. Systems for flow rate and pressure drop monitoring of the ventilation systems serve as an additional control measure for environmental and worker safety compliance [40]. According to data from 2015 released by First Solar, Cd emissions to air in U.S. in form of CdTe accounted for 9.56×10^{-6} g per m^2 module [41]. The Cd levels in manufacturing wastewater are approximately 3.62×10^{-5} g per m^2 module [41]. This corresponds to airborne emissions of 52 g Cd/GW of rated power, or 1.2 mg Cd/GWh, and waterborne Cd of 199 g/GW or 4.6 mg/GWh (based on 1800 kWh/m^2 insolation and on the 18.2% efficiency of First Solar's 2019 vintage modules).

First Solar's Industrial Hygiene Management Program for cadmium management is extensive and includes occupational exposure limits that are much more stringent than those required for regulatory compliance. Cd concentration levels indoors the manufacturing facility are continuously monitored: the 8-hr time-weighted average (TWA) concentrations during normal operations were always below 0.11 $\mu g/m^3$ which are one order of magnitude below First Solar's action level of 1 $\mu g/m^3$ and 50 times below the OSHA Permissible Exposure Limit (TWA-PEL) of 5 $\mu g/m^3$ limit. Cadmium level shows transient elevation at surrounding area only during equipment preventive maintenance activities. Additional controls and personal protective equipment applies during such activities to control exposure below First Solar Action Level of 1 $\mu g/m^3$ [95]. In addition to air and effluent monitoring, long-term bio--monitoring has demonstrated the efficacy of the engineering controls in place. Blood and urine testing shows employee exposure to cadmium is far below OSHA action levels and show a statistically significant decreasing trend as a function of years worked for non-smokers [42].

As discussed in the Introduction, the cumulative energy demand (CED) of the life-cycle of CdTe PV is much lower than that of any other commercial PV technology. More specifically, the life-cycle cumulative energy demand (CED) of manufacturing a CdTe PV module is 848.7 MJ/m^2, whereas a monocrystaline-Si module requires 23620 MJ/m^2 and a multi-crystalline PV module consumes 2295 MJ/m^2. By including the BOS, a full CdTe PV system of 15.6% efficiency consumes an input of 10,773 MJ/kW, whereas that for monocrystalline–Si PV of 17%

Table 1
Physico-chemical, and toxicological properties of CdTe [34].

Category	Test	Result
Physico-chemical properties	Physical state	solid at 20 °C and 101.3 kPa
	Melting/freezing point	1042 °C at 101.3 kPa
	Relative density	5.83 g/cm^3
	Granulometry	The volume mean diameter of the substance is 155.67 μm, (weighted respirable fraction is 0.0% by SWeRF analysis)
	Water solubility	19 μg/L after 28 days at 22 °C with 1 mg/L loading
	Solubility product	9.5×10^{-35}
Bioaccessibility	Gastric	1.5%
Acute toxicity	oral	No adverse effect observed LD50: >2000 mg/kg bw (rat)
Acute toxicity	inhalation	Adverse effect observed LC50: 2710 mg/m^3 (rat)
Irritation/Corrosivity	skin	No adverse effect observed (not irritating) (rabbit)
Irritation/Corrosivity	eye	No adverse effect observed (not irritating) (rabbit)
Sensitisation	skin	No adverse effect observed (not sensitising) (guinea pig)
Repeated dose toxicity	inhalation	Adverse effect observed LOAEL: 3 mg/m^3 (28 day; rat)
	oral	No adverse effect observed NOAEL: 1500 ppm in diet (14 day pilot study; rat)
Mutagenicity	in vitro/in vivo	No adverse effect observed (negative) (bacteria, mouse lymphoma cells, Chinese hamster lung fibroblasts)
Reproductive toxicity: effects on fertility	oral	No adverse effect observed (rat) NOAEL: 100 mg/kg body weight/day by gavage (28 day; rat)
Reproductive toxicity: developmental toxicity	oral	No adverse effect observed (rat) NOAEL: 100 mg/kg body weight/day by gavage (28 day; rat)
Acute aquatic ecotoxicity	Species	LC50 (mg CdTe/L)
	Fish: *Danio rerio*	>1000
	Invertebrate: *Daphnia magna*	1.14
	Algae: *Pseudokirchneriella subcapitata*	3.1
Chronic aquatic ecotoxicity	*Daphnia magna*	0.2
	Pseudokirchneriella subcapitata	0.37
Terrestrial ecotoxicity	Species	NOEC (g Cd Te/kg DW)
	Worm: *Eisenia fetida*	2.1
	Soil-dwelling springtail: *Folsomia candida*	0.01
	Dicot seedling: *Lepidium sativum*	2.1
	Dicot seedling: *Phaseolus vulgaris*	2.1
	Monocot seedling: *Secale cereale*	2.1
	Soil microbial activity	2.1

Abbreviations:

LD50	50th percentile lethal dose
LC50	50th percentile lethal concentration
LOAEL	lowest observed adverse effect level
NOAEL	no observed adverse effect level
NOEC	no observed effect concentration

The following definitions are taken from Ref. [35].
[1] *LC50* is the concentration of a substance in an environmental medium that causes the death of 50% of the population of animals tested following following a certain period of exposure.
[2] The *lowest-observed-adverse-effect level (LOAEL)* is the lowest concentration or amount of a substance found by experiment or observation that causes an adverse alteration of morphology, function, capacity, growth, development, or lifespan of a target organism distinguished from normal organisms of the same species under defined conditions of exposure.
[3] The *No-Observed-Effects-Concentration (NOEC)* is the greatest concentration that causes no alteration of morphology, functional capacity, growth, development or life span of a target organism distinguished from normal organisms of the same species under defined conditions of exposure.
[4] *LD50* is the amount of substance or agent that causes the death of 50% of the population of animals tested when taken into the body.

efficiency uses 26,190 MJ/kW and for multi-Si PV of 16% uses 19,543 MJ/kWp [83]. It is noted that the reported efficiencies represent 2016 averages, and that, since then efficiencies of these PV technologies have increased by about 15%, and thus the per kW CEDs are correspondingly lower than those reported in 2016.

Water consumption and waste generation continue to decline as First Solar upgrades manufacturing processes and engineering controls at its production facilities. Over 80% of material sent offsite is being sent for beneficial reuse rather than landfill [37]. Furthermore, commercial-scale recycling facilities are installed at each First Solar manufacturing site to handle the small percentage of modules that are scrapped, as well modules that have been returned as part of First Solar's voluntary recycling services [37]. Ongoing improvements in pulsed direct current magnetron sputtering may enable deposition of layers as thin as one micron, further reducing material utilization [39]. First Solar continues to set efficiency records and maintain competitiveness with silicon PV technologies; current commercial module efficiency is 17.2% and record module efficiency is ~20% [43].

5. Product use

As outlined in the IEC 62994 technical specification on PV environmental health and safety risk assessment, some stakeholder concerns associated with the use phase of PV systems are potential emissions of hazardous materials during non-routine events such as fire and field breakage [44]. These scenarios are considered below.

5.1. Fire risk

One stakeholder concern for rooftop PV installations is fire, as buildings are made of flammable materials. Proper installer training and rigorous material codes and standardizations can minimize PV-related fires [45]. With regard to frequency of fire events involving PV modules, almost all involving Si panels, researchers in Italy, for example, identified about 600 Italy-wide fires involving solar panels in 2012. These events, which followed the first high volume wave of installations in the country, decreased in subsequent years. The researchers of Fiorentini et al., 2016 note that this decrease was concurrent with the enactment of national codes and standards, which were previously lacking in Italy, and with PV panel producers' incorporation of fire prevention requirements in their user manuals and installation guides [45]. It is noted that Si-based PV modules are typically encapsulated with one glass and one polymeric sheet (e.g., Tedlar) and the later is combustible, whereas CdTe PV modules are encapsulated within two sheets of glass.

Whether or not a PV system is directly involved in fire ignition, though, modules may modify the path of fires outside or through buildings due to their altering of smoke and venting systems, for example, and pose an electrical hazard to firefighting personnel [46]. Best practice guidelines for fire prevention and firefighter safety have been developed by the International Energy Agency [47,48], along with methods for conducting human health risk assessment of emissions from PV fires.

Early studies, lacking empirical data, assumed, parametrically, that mass fractions up to 100% of the total mass, could be emitted during a residential rood-top fire [49]. Later on, experiments were performed by Brookhaven National Lab (BNL) that comprehensively assessed Cd emissions from CdTe PV modules exposed to fires [50]. The experiments showed that almost all (i.e., 99.5%) of the cadmium content of CdTe PV module pieces (25 × 3 cm) was encapsulated in the molten glass matrix after module glass fused together. As such, very little Cd escaped the PV panel structure during a controlled burn. Whereas the BNL experiments utilized a tube furnace, a recent PV fire emissions study by TÜV Rheinland and Fraunhofer ISE [46] exposed the underside of mounted PV modules to fire flames with a gas burner. Based on measured emissions to air of 29 mg Cd per CdTe PV module, and given approximately 6 g of total Cd content per module [51], the percentage of Cd emissions to air was 0.5%, consistent with the BNL results.

In addition to experimental fire testing, worst-case modeling was conducted by the Bavarian Environmental Agency assuming total release of Cd content in CdTe PV modules from rooftop building fires. Based on Gaussian dispersion modeling, downwind ground-level Cd concentrations were below human health screening levels [52].

As reported by the IEA-PVPS [94], several of the world's largest solar facilities utilize thin film CdTe PV on ground-mount utility-scale power plants (e.g., Desert Sunlight, Topaz, Agua Caliente, El Centro, Campo Verde, Templin, Copper Mountain). Also, First Solar's business reports highlight the company's focus on utility-scale project development for corporate and utility customers [96]. For these ground-mount PV installations, vegetation is limited to grass to minimize shading, thereby limiting fuel load. Grass fuels have short flame residence times (~15 s), and maximum temperatures are approximately 800–1000 °C [53], below the melting point of CdTe and of module glass.

5.2. Extreme weather conditions

Aside from the potential for emissions through fires, emissions may result from extreme weather. Breakage followed by precipitation may result in leaching from modules and subsequent impact to soil, air, or groundwater. In an early thin-film PV module experiment, Steinberger measured leachate from broken CdTe PV module pieces in an outdoor experiment with actual rainwater, finding no critical increase in soil Cd concentrations after one year of leaching [54]. Since then, several non-standard leaching tests have utilized finely ground samples and/or extended extraction cycles [55–57], which can provide data on the total quantity of metals in a sample, but not their availability under realistic field breakage conditions [58]. The standard leaching test, USEPA Method 1312 Synthetic Precipitation Leaching Procedure (SPLP), measures the mobility of analytes in simulated rainwater with methods similar to the USEPA Method 1311 Toxicity Characteristic Leaching Procedure (TCLP) used for waste characterization (Table 3).

In addition to leaching experiments, Sinha et al., 2012, modeled leaching risks using a worst-case mass balance approach, where all of the Cd in each broken module was assumed to be transferred via rainfall during a given exposure period. Even with this conservative approach, modeled impacts to soil, air, and groundwater were well below human health screening levels for all forms of Cd intake (i.e., inhalation, ingestion, etc.) [51]. As such, Cd transported from broken panels by rainwater is highly unlikely to pose health risks to residents, workers, consumers, or emergency responders. Like with fires, then, while there may be Cd emissions under extreme conditions, any such release would not pose a serious environmental, health, or safety concern at any given installation location. A broader discussion of Cd leaching risk tied to CdTe panels is discussed later as part of the panel's end-of-life. Note that once a panel is broken, it will be deemed fit for removal and/or replacement for both commercial and safety reasons, given the subsequent loss of power output from broken modules. In addition to removing modules broken during installation, operations and maintenance procedures are used to identify and remove broken modules during system operation, through routine inspections, power output monitoring, and response and cleanup following extreme weather events (see Fig. 3).

In addition to leaching experiments and worst-case modeling, data from actual weather events can inform risks related to breakage. In 2015, a tornado impacted a California PV facility which utilizes CdTe PV modules, damaging 1.8% of the modules (Fig. 4). The damaged panels were collected, over 85% were recycled, and the remainder were disposed of based on composite sampling of soil and module pieces from the tornado event which passed TCLP tests [59].

The damaged panels were collected, over 85% were recycled, and the remainder were disposed of based on composite sampling of soil and module pieces from the tornado event which passed TCLP tests [59]. Actually, this has been a common practise in all huricane affected solar farms; thus the. damaged PV modules were collected and recycled or disposed according to local regulations (Fig. 5).

With respect to hurricanes, PV systems have a reputation of being very resilient. During hurricane Sandy (2012), which left 8.5 million people across the East Coast without power [60], almost every PV system was left undamaged [61]. Similarly, very little damage was found after Hurricane Florence in 2018 [62]. This is because PV's certification for wind speed is usually 225 km/h (it is 257 km/h in Florida where

Table 2
Focus areas for PV survival under hurricane conditions [54,58].

Critical PV Survivability Factors	Proposed Solution(s)
Loose fasteners vulnerable to vibrations	Use properly torqued and locked fasteners
Inadequate module clamping fasteners	Use through-bolting modules instead
Low module resistance to wind	Increase resistance capabilities through vibration-resistant connections
Weak mounting structure	Use a three-frame rail system to provide lateral racking support (and prevent module bending and twisting)
	Use closed-form (tubular) frame elements with low drag coefficients (as opposed to open-shaped "C" and hat channels)
	Use stainless steel to prevent corrosion and material weakening

Table 3
Summary of Regulatory Leaching Test Methods and Results for CdTe PV modules [58].

Geography	United States	United States	Germany	Japan
Leaching Test	U.S. EPA Method 1311 (TCLP)	U.S. EPA Method 1312 (SPLP)	DIN EN 12457–4:01-03	MOE Notice 13/JIS K 0102:2013 (JLT-13)
Test type	Waste Characterization	Rainwater leaching	Waste characterization	Waste characterization
Sample size (cm)	1	1	1	0.5
Sample preparation	Water-jet cutting	Water-jet cutting	Water-jet cutting	Hammering
Solvent	Sodium acetate/acetic acid (pH 2.88 for alkaline waste; pH 4.93 for neutral to acidic waste)	H_2SO_4/HNO_3 (60/40 wt %); pH 4.2	Distilled water	Distilled water
Liquid:Solid Ratio	20:1	20:1	10:1	10:1
Treatment Method	End-over-end agitation (30 ± 2 rotations per minute)	End-over-end agitation (30 ± 2 rotations per minute)	End-over-end agitation (5 rotations per minute)	End-over-end agitation (200 rotations per minute)
Test Temperature	23 ± 2 °C	23 ± 2 °C	20 °C	20 °C
Test Duration	18 ± 2 h	18 ± 2 h	24 h	6 h
Leachate Cd Concentration for CdTe PV (mg/L)	0.22	0.016–0.019	0.0016–0.0040	0.10–0.13
Regulatory Cd limit (mg/L)	1	Not applicable	0.1	0.3

Fig. 4. First Solar's Desert Sunlight section damaged by tornado on July 28, 2015 (source: https://www.kesq.com/news/solar-farm-damaged-by-desert-center-tornado/62923230).

Fig. 5. Damaged panels, frames and mounts are seen at the 24-MW Illumina solar plant in Puerto Rico collected for recycling. (Source: Maria Gallucci/IEEE Spectrum).

hurricanes are frequent), which is higher than the wind speed of most hurricanes (Sandy's maximum wind speed was 185 km/h and Florence's was 220 km/h, although it made landfall as a weakened Category 1 hurricane). In the case of Category 5 Hurricane Maria in Puerto Rico in 2017, the Sonnedix Horizon facility which utilizes CdTe PV modules (Salinas Solar Park) had only minor PV module damage. Of the installation's 167,832 modules, only 872 were damaged (0.52%) [63]. In the case of Hurricane Michael in 2018 which has retroactively been upgraded to category 5 at time of landfall in Florida [64], no PV module damage was observed at the solar facility of GameChange Solar in Tallahassee, FL utilizing CdTe PV modules [65].

Field examinations of damaged PV installations following the 2017 hurricane season have revealed some potential critical factors that affect the survivability of a PV system during a hurricane (or a similar extreme weather event). These problems and proposed solutions have been investigated by multiple researchers, including a team out of the Rocky Mountain Institute [66,67]. Their findings and recommendations are summarized in Table 2.

Subsequent to some degradation problems with series 4 mounting clips, First Solar issued a list of approved retaining clips for this and previous module series [97] the report Approved retaining clips for Series 4, "First Solar does not test clip longevity nor take responsibility for long-term performance. Compatibility with Series 4 modules is issued only with respect to tests outlined in PD-5-320-04. "The document adequate is "http://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-4-Application-Note/FS-Series-PV-Module-Mounting.ashx?la=en". Furthermore, the transition from Series 4 to Series 6 involved a transition from frameless Series 4 modules installed with clips to framed Series 6 modules that do not require clips [97].

6. End-of-Life

An assessment of sustainability in the life cycle of CdTe PV must conclude with an analysis of the end-of-life of CdTe panels. More specifically, given concerns about Cd emissions associated with CdTe panels, we must consider how such panels will reasonably be managed at the end of their useful life and what Cd emissions may result from each management option.

End-of-life management is less of an immediate concern today due to the relatively low volume of CdTe PV panels reaching the end of their useful life, as PV panels have a long lag time from the time they are produced to the time they are decommissioned (25–30 years) [68]. As PV waste accumulates at the end of this time lag, there will be considerable growth in PV waste as forecasted by the International Renewable Energy Agency and International Energy Agency [69]. Thus, the end-of-life management of CdTe PV is a matter that must be understood today to prevent sustainability problems in 25 years. To address this, we divide the end-of-life management options into two parts. The first focuses on the disposal of CdTe panels in municipal solid waste streams as an end-of-life option. The second analyzes the recycling of CdTe panels at their end-of-life as an alternative to disposal.

6.1. Disposal of CdTe

In the absence of a regulatory scheme that mandates recycling, PV modules may be disposed of in accordance with general waste law in a given jurisdiction. In the European Union, the WEEE Directive mandates PV recycling [70], and in the United States, the state of Washington passed Senate Bill 5939 which requires a takeback and recycling program for end-of-life PV modules [71]. In the absence of recycling regulation, PV modules may be disposed as non-hazardous or hazardous waste depending on their waste classification. Table 3 shows results from standard leaching tests in various regions that are used to characterize waste.

Experimental leaching evaluation of disposal of CdTe panels into simulated landfills suggest different impacts dependent on the phase of the landfill itself, with limited leaching potential under anoxic (reducing) conditions regardless of pH and higher leaching potential under aerobic, acidic conditions [72]. These results are consistent with the commercial CdTe PV recycling process which utilizes a combination of strong acid (H_2SO_4) and strong oxidizing agent (H_2O_2) to leach semiconductor material [73]. However, it is important to note the condition of the panel in the leaching study is inconsistent with how panels will reasonably be disposed of in MSW streams. The study also differs from the standard leaching test methods in Table 3 which are applicable to all waste types, and it utilizes non-encapsulated PV technology which is not representative of current commercial PV products. To place CdTe panel fragments in leaching columns, the panels were first broken by hammer and in a milling process. CdTe film is not brittle and the panel was poorly fragmented after these processes. Thus, the panel was further broken by hand and the CdTe film was separated from the glass [72]. The resulting fragments of CdTe were only a few mm wide and non-encapsulated, which is non-representative given previous landfill experiments on commercial PV modules which showed the glass-encapsulant-glass structure maintained after landfill compactor crushing [74]. The leaching potential of Cd from the CdTe panel is limited by the glass-adhesive laminate-glass structure of the device that encapsulates the semiconductor material [75] and artificially removing the glass is not a realistic condition of current commercial panel disposal. Given the manual work that was done in the leaching studies to create those conditions [72], it is unlikely a CdTe panel with tempered glass would be reduced to such conditions within an MSW stream and so the leaching studies overestimate the potential Cd emissions from CdTe panels.

Other research into the disposal of CdTe panels into landfills has focused on the human health impacts of such disposal pathways. Screening-level, fate and transport, modeling techniques evaluated health risk for ingestion of contaminated groundwater [76], which can potentially result from the leaching of Cd from CdTe panels into groundwater below a MSW landfill if the landfill is unlined or improperly managed. The screening-level assessment further determined that an annual CdTe PV waste volume of 1900 m^3, or approximately 354,000 panels, disposed of into a single landfill for 20 years would warrant a more thorough risk assessment using the TCLP limit of 1 mg/L [76]. This waste volume could reasonably be absorbed by a large landfill but to exceed the estimated critical waste volumes a single landfill would have to absorb greater than 4% of the total amount of CdTe PV panel waste generated from recent production volumes every year for 20 years [76]. This is an unlikely scenario unless CdTe PV panels are disposed of in only a few landfills and those landfills are unlined, which indicates the risk of adverse health impacts from groundwater contamination with Cd from CdTe PV panels in landfills is acceptably low at current CdTe production volumes [76].

The third disposal pathway in MSW streams is incineration of the CdTe PV panels if they are not identified and removed prior to incineration. This is the only disposal pathway with direct Cd emissions to air. In a study of different disposal pathways, it was found that leaching to water of Cd from CdTe PV panels in landfills is approximately 0.09 g/kg of Cd content in the panels, whereas the direct Cd emissions to air resulting from incineration of CdTe PV panels in MSW incinerators can be 5 g/kg of Cd content [77]. However, in the total analysis of CdTe PV panel disposal pathways, incineration represents only a small fraction of total waste volumes given that incineration occurred for only 12.8% of the total MSW stream in the U.S. in 2015 [78]. For utility-scale PV systems, decommissioning plans developed during the permitting of solar facilities specify end-of-life recycling of PV modules and balance of systems, including residual value from recycling, making MSW incinerators an unlikely end-of-life treatment option. As such and because of the low calorific value of PV modules which are predominantly composed of glass and aluminum by weight, MSW incinerators are not considered a likley end-of-life disposal pathway.

6.2. Recycling CdTe

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 [98]. Current recycling programs for c-Si PV aim at bulk recycling, thus recovery of high-mass fraction materials such as glass [99], aluminum and copper. However, CdTe PV recycling also aims at recycling the semiconductor materials (e.g., Te, Cd) which add to the value of recycling. CdTe PV modules have been treated in dedicated recycling plants integrated with module production plants, where the semiconductor materials are recovered in addition to glass and copper [100]. In 2015, First Solar developed its 3rd generation recycling technology which achieves recovery of pure glass and semiconductor and metals mixtures in a continuous-flow process with a recycling capacity of 150 metric tons per day [101].

Commercial CdTe PV recycling involves two main steps, mechanical crushing of PV panels with shredder and hammer-mill, and wet chemical processing to separate semiconductor from glass using strong acid and oxidizing agent (dilute sulfuric acid and hydrogen peroxide, respectively). Emissions to air (5.89×10^{-9} kg Cd per m^2 module) have been managed with enclosed equipment and HEPA filtration and emissions to water (8.92×10^{-8} kg Cd per m^2 module) have been managed with onsite wastewater treatment [79]. With regards to occupational health, biomonitoring of CdTe PV workers, including both manufacturing and recycling operations, show a statistically significant decreasing trend of blood and urine Cd as a function of years worked for non-smokers [42].

Commercial yield for CdTe PV recycling exceeds 90% for glass and semiconductor recovery [80], and research suggests that recycling can potentially recover 99.99% of the Cd in the CdTe PV panels using ion-exchange resins [81]. In this way, recycling is the favored management option when compared to disposal for end-of-life CdTe PV panels to avoid unintentional Cd emissions in an MSW landfill or MSW incinerator. In addition, recycling maximizes resource efficiency and can mitigate some of the risks outlined in the above section on Raw Materials by providing a source of Te for future CdTe PV manufacturing [82] (Fig. 6).

In addition to efficient separations technology, other factors that affect the viability of PV recycling are effective collection schemes, customers for the products of recycling, and regulations on the handling and transport of waste (Fig. 7). Studies on decommissioning, collection and recycling of end-of-life CdTe PV power plants showed that recycling can be profitable by optimizing the collection and recycling plant locations [102–105].

7. Conclusion

This paper updates an earlier (2004) review of the sustainability of thin-film CdTe PV, with data reflecting research and deployment over

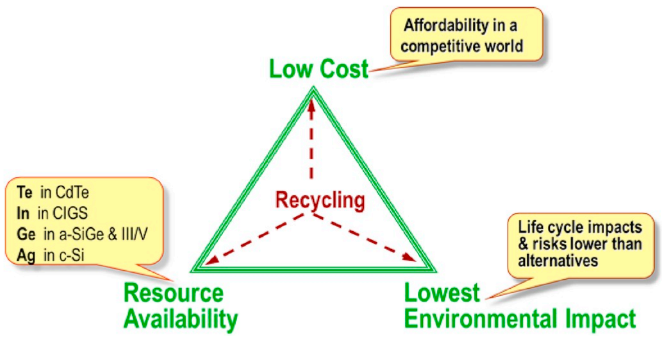

Fig. 6. Recycling enhancing the three pillars of sustainability. The three pillars of sustainable PV growth.

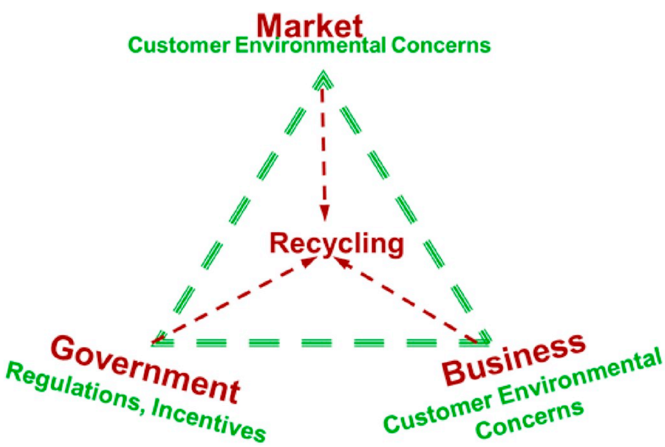

Fig. 7. Recycling addressing public concerns and regulatory requirements.

the past 15 years in order to compare precautionary concerns about the technology with actual performance given that 25 GW of PV modules have been deployed globally since the time of the first review. Naturally, the focus is on First Solar's CdTe PV modules and systems, the major manufacturer of CdTe PV modules and designer of large PV power plants. The findings of this study are summarized as follows:

All published LCA studies concur that thin-film CdTe PV is advantageous across all environmental impact categories, to currently commercial PV technologies, as it requires the least amount of energy during module production.

Recent studies showed that the potential ecotoxicity of CdTe is three orders of magnitude lower than that of Cd. It also shown that First Solar's Industrial Hygiene Management Program for cadmium management is extensive and includes occupational exposure limits and effluent controls that are much more stringent than those required for regulatory compliance. In addition to air and effluent monitoring, long-term biomonitoring has demonstrated the efficacy of the engineering controls in place.

Water consumption and waste generation continue to decline as First Solar upgrades manufacturing processes and engineering controls at its production facilities. Commercial-scale recycling facilities are installed at each First Solar manufacturing site to handle the small percentage of modules that are scrapped, as well modules that have been returned as part of First Solar's voluntary recycling services.

Fire risk is a concern for rooftop PV installations, as buildings are made of flammable materials and several fire events involving PV modules have been reported in Italy. These events, which followed the first high volume wave of installations in the country in 2012, decreased in subsequent years as proper installer training and rigorous material codes and standardizations materialized. It is noted that these fire events were associated with Si-based PV modules which are typically encapsulated with one glass and one polymeric sheet (e.g., Tedlar) and the latter is combustible, whereas CdTe PV modules are encapsulated within two sheets of glass. It is also noted, that First Solar market focus is ground-mount utility-scale PV installations, not roof-top residential ones. For such installations vegetation is limited to grass, thereby limiting fuel load. Grass fuels have short flame residence times, and maximum temperatures are well below the melting point of CdTe.

In case that CdTe PV modules are involved in roof-top fires, analytical and experimental studies at Brookhaven National Laboratory in 2003–2004 have showed that very little Cd (i.e., 0.05%) escaped the PV panel structure. Recent PV fire emissions studies by TÜV Rheinland and Fraunhofer ISE confirmed these findings.

Another concern is leaching of elements from broken modules. Some studies alerting to cadmium leaching risks used completely invalid assumptions, e.g., grinded and/or un-encapsulated modules, whereas the most comprehensive studies showed absolutely no risks during normal conditions and insignificant risks during extreme conditions like major storm events.

Tellurium is a minor metal in the production of copper and its availability is limited by the production rate of the base metal. Demand side management strategies have led to more than 50% reduction in the semiconductor intensity of CdTe PV modules since 2004, and additional reductions are expected with further increases in material utilization and module and system efficiencies. A combination of primary and secondary –from recycling-production could would enable annual production of CdTe PV on the order of 100 GW/yr by mid-century at reasonable cost, which would enable result in TW-scale deployment on the order of a decade. Given the 25–30 years lifetime of PV panels, end-of-life management will become a concern by approximately 2030–2040. Of various end-of-life options, CdTe PV recycling is commercially available and minimizes potential environmental impacts in comparison to landfill disposal or incineration, while allowing for semiconductor recovery for further manufacturing of CdTe PV panels.

Overall, CdTe PV panels satisfy the main components of eco-efficiency – cost competitiveness and low life cycle environmental impact – and we expect they will continue to do so in the future given continuous improvement in product design, testing, and stewardship.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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