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Cadmium Sulfide-buffered Photovoltaic Systems: Assessing the Environmental, Health, and Economic Impacts

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Running Title: Cadmium Sulfide-buffered PV Systems

Abstract

As the world's population continues to grow, it is expected that global energy demand will also continue to rise in the future. This projected growth in energy demand coupled with increasing awareness on carbon emissions and global climate change associated with the use of fossil fuels has accelerated the demand for various renewable energy technologies, including solar photovoltaics (PV). PV technology is currently undergoing a transformation with development of several thin film technologies such as perovskite solar cells which not only offers higher efficiency and scalability, low-cost production, but also non-toxicity and stability. Cadmium sulfide (CdS) is a widely used buffer material in thin film PV, which has significant advantages over other alternate buffer materials in terms of efficiency and low-cost of production for large-area processing of thin films. However, the potential environmental risks associated with the use of cadmium are of concern. In this paper, we assess and monetize environmental, health, and socio-economic externalities associated with the use of CdS. We quantified the environmental, human health, and socio-economic impacts of cadmium emissions from CdS-buffered PV system. In addition, this paper provides a comprehensive outlook of the past, current, and future global market growth rate of thin film PV technologies.

Introduction

Solar PV technology converts solar energy directly into electrical energy using the optoelectronic properties of the suitable semiconductor materials. Buffer layers are commonly used in optimization of thin film solar cells by forming a reliable p-n junction with the absorber layer and allowing maximum transmission of light (minimum absorption loss) to the junction region and the absorber layer (Friedlmeier *et al.* 2017). Buffer layers passivate the junction material, providing a layer of appropriate thickness and index of refraction that

reduces the overall reflectance, while avoiding shunts between the absorber and the front electrode (Mughal *et al.* 2015; Wennerberg 2002).

Figure 1 illustrates the structure of the solar cell that utilizes n-type CdS and p-type cadmium telluride (CdTe) as buffer and absorber materials respectively. The buffer layer is sandwiched between the absorber layer and the anti-reflection coating (ARC). A rear contact (highly transparent conducting oxide, such as tin oxide) and a front contact (metal electrode, such as nickel or aluminum) are used to carry excited electrons in the conduction band, across the junction from the n-type to the p-type semiconductor, to an external load. These electrons then dissipate their energy into an external circuit and returns to the rear contact of the

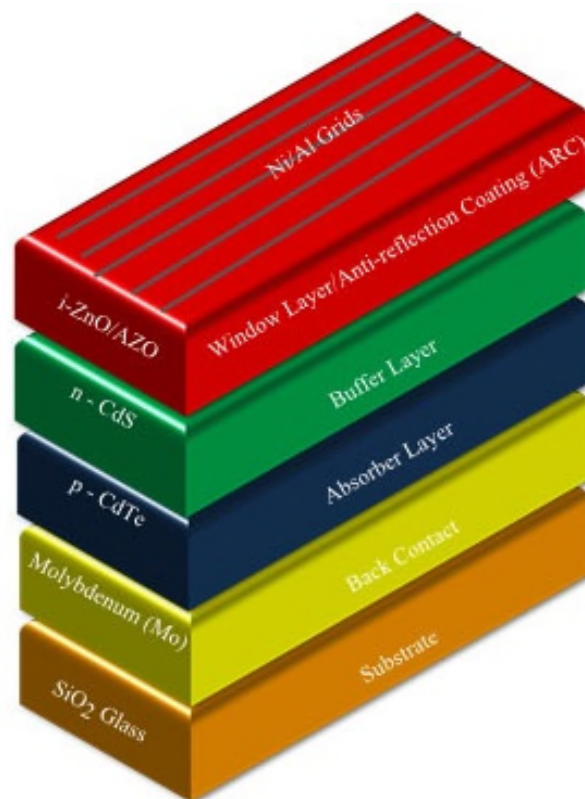


Figure 1. n-CdS/p-CdTe PV cell structure.

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PV cell (Oladeji 2000; Mughal *et al.* 2014). The absorber layer constitutes the core of any PV device; however, the junction interface properties between the absorber and buffer layers are also quite significant to the performance of the device (Hultqvist 2010). The interfacial properties of buffer layer affect efficient charge separation and transfer.

CdS is the oldest and most widely known buffer material which was initially used in solar cells for aerospace applications back in the 1950's (Reynolds *et al.* 1954). It is an important n-type semiconductor material with an optical bandgap of 2.42 eV (Naghavi *et al.* 2010). The commercially available CdTe and copper indium gallium diselenide/copper indium diselenide (CIGS) technologies utilize CdS buffer layer to form a heterojunction interface (Rix *et al.* 2015). Chemical bath deposited (CBD) CdS-based PV devices yield good performances, however, there are drawbacks concerning industrial-upscaling from the use of the carcinogen thiourea and hazardous cadmium (Cd) in large amounts (Paris and Gmbh 2005). CBD encompasses a variety of routes for synthesizing thin films at a relatively low temperature by immersing a substrate in a liquid solution (Feitosa *et al.* 2004). The process involves generation of S²⁻ ions in the presence of an aqueous alkaline bath containing a Cd salt, which results in the precipitation of CdS. Deposition of CdS is based upon the reaction between the precursors in a metastable condition allowing large area processing with low fabrication costs (Mughal *et al.* 2015). Other depositions techniques such as atomic layer deposition (ALD) and sputtering are quite expensive as compared

to the CBD. Several studies have emphasized upon the replacement of CdS in chalcopyrite PV devices due its toxicity (Hultqvist 2010; Naghavi *et al.* 2010; Paris and Gmbh 2005). However, the PV industry is reluctant to replace CdS, as it is a proven cost-effective material which can reach energy conversion efficiencies of 23.3% for a 0.5 cm² laboratory cell (Green *et al.* 2017). Although research is underway to evaluate alternatives for CdS, the most efficient heterojunction PV devices still utilize a CdS buffer layer (Ward *et al.* 2014). Table 1 summarizes the operational performance of CdS-buffered PV systems synthesized by different deposition techniques.

The toxicity of Cd compounds (CdTe, CdS, etc.) is well documented (T.E.P.A.T.C.O and European Union 2003). They can enter the environment from many different sources such as manufacturing site, landfills, incinerators, etc. These chemicals can move through air, soil, and water contaminating the environment. Human exposure to these hazardous chemicals by inhalation, ingestion, or skin contact poses a great risk to human health and social conditions (Tchounwou 2012). The toxicity of Cd first came to light with the outbreak of "itai-itai" disease in Japan in 1950's (Kasuya *et al.* 1992). This disease caused severe pain, and discomfort in bones and joints. This happened when the runoff water from the mines containing large concentration of Cd was used in irrigation of various crops. Cd was absorbed by the crops and passed on to the humans resulting in various diseases including kidney failure (White and Chaney 1980). Since that time there has been a gradual increase in awareness regarding adverse

Table 1. Operational performance of cadmium sulfide (CdS)-buffered TFP devices utilizing different deposition techniques.

Deposition technique	Efficiency [%]	Current density, J _{sc} [mA/cm ²]	Open circuit voltage, V _{oc} [mV]	Fill factor, FF [%]	Area (cm ²)
Atomic Layer Deposition (ALD) (Hultqvist <i>et al.</i> 2007)	16.7	32.8	671	75.8	0.5
Chemical Bath Deposition (CBD) (Green <i>et al.</i> 2017)	23.3	32.98	621	74.7	0.5
Physical Vapor Deposition (PVD) (Rusu <i>et al.</i> 2005)	14.1	31.4	610	73	0.5
Sputtering (Gupta and Compaan 2004)	14	23.6	814	73.25	0.3
Ultrasonic Spray Pyrolysis (USP) (Fella <i>et al.</i> 2010)	12.5	30.3	570	73	0.3

impacts of Cd to human health.

In 1993, the International Agency for Research on Cancer (IARC) classified Cd as Category 1 human carcinogen (IARC 1987). Later, the National Toxicology Program (NTP) conducted an independent assessment and concluded that Cd and Cd-compounds are human carcinogens (Huff *et al.* 2007). As PV production ramps-up, this will speed-up the mining process for the extraction of these compounds, increasing emissions and metal leakage from waste dumps into the air, soil, and water. Clean and sustainable energy is the enabler for the welfare and economic development of a society. Solar PVs have the potential to meet these energy requirements and we've seen rapid growth during past two decades. With large scale adoption and deployment of the new PV energy systems, it is imperative to comprehend their impacts on environment and human health.

In this paper, the primary goals of our study were threefold: (1) investigate emissions from CBD CdS buffer layers during the life cycle of PV cells, and the potential for Cd release into the environment; (2) examine potential environmental and health risks related to manufacturing and disposal of CdS-buffered PV systems; and, (3) assess and monetize environmental, health, and socio-economic externalities associated with use of CdS-buffered PV systems.

Global PV Market Share and Growth

The sun emits 3.8×10^{26} Watts (W) of power, with a corresponding amount of energy produced each second equaling 3.8×10^{26} joules (J) (University of Minnesota 2014). The amount of energy that the sun produces in an hour can meet the annual energy needs of the whole planet, whereas the energy stored in the earth's known reserves of fossil fuels corresponds to only 20 days of sunshine (Forsberg 2009). In economic terms, we have already wasted a huge amount of the energy resource.

PV production has increased dramatically since 2005 in the United States, reaching 40 gigawatts (GW) of installed PV capacity in 2016 from five gigawatts (GW) in 2005, with global installed capacity reaching 320 GW (Philipps *et al.* 2017). According to the International Energy Agency's (IEA) Technology Roadmap on Solar Photovoltaic Energy (2014 Edition), the PV share in global electricity productions could reach 16% by the end of 2050 with installed PV capacity reaching 4.512 TWs. While world's energy growth in consumption is expected to reach 33 terawatts (TWy) (IEA 2014). Figure 2 shows the trend of increase in

installed global PV capacity.

PV is the fastest growing market with compound annual growth rate (CAGR) of PV installations of 40% between 2010 and 2016 (Philipps *et al.* 2018). In 2016, Europe's contribution to the cumulative PV installations amounted to 33% compare to 26% for China and Taiwan (Philipps *et al.* 2017), however, China is expected to take the lead soon after 2020. Latin America, Africa and the Middle East, and OECD Pacific will continue to increase their PV market share. From 2030 to 2050, the PV share of India and other Asian countries is expected to rise from 13% to 25%. In contrast, the U.S. share is expected to remain near 15% from 2020 onwards, and Europe's share to decrease constantly from 44% in 2015 to 4% in 2050 mainly due to growing PV capacity in other parts of the world. By the end of 2050, Africa and the Middle East will have the largest share of global PV production (IEA 2008).

Thin Film Photovoltaics Share and Growth

TFP technologies are subdivided into three main families: (1) amorphous (a-Si) and micromorph silicon (a-Si/ μ c-Si); (2) cadmium-telluride (CdTe); and, (3) Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

After early years of steady increase in TFP technology share, in 2016, the global PV market production share of all TFP technologies amounted to about 6% (4,900 MWp) of the total annual production falling from 13.2% in 2010 and 11.5% in 2012 (Philipps *et al.* 2017; Philipps *et al.* 2018). Figure 3 illustrates the timeline of global PV market share of TFP technologies from 2000 to 2016. This also reflects the challenges faced by TFP technology given significant cost reductions and efficiency improvements experienced by crystalline silicon (c-Si) in 2011 and 2012. Of that 6%, the market share for CdTe and CIGS technologies is

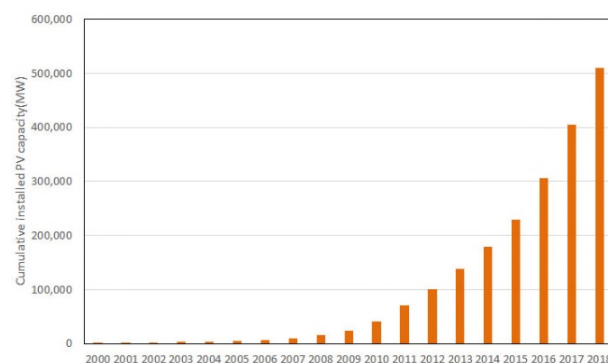


Figure 2. Cumulative installed global PV capacity 2000-2018 (Data adapted from Statista 2019).

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respectively 3.9% (3,100 MWs) and 1.8% (1,300 MWs) (Philipps *et al.* 2017; Philipps *et al.* 2018) in which CdS is deployed as a buffer material (GBI 2012). Global PV cumulative installed capacity for CdS-buffered PV systems installation between 2000 and 2016 was 20,746 MWs (Table 2).

First Solar Corporation has approximately 90% of the market share of CdTe technology, with majority of market share being in North America, as the usage of Cd in the European Union (EU) is highly regulated. Hanergy Thin Film Power has about one-third of the market share of CIGS technology and a majority of its share is in Asia-Pacific and European markets (Research and Markets 2014). Amorphous silicon's (a-Si) share within TFP had rapidly increased in past (Campillo and Foster 2008); however, the focus is gradually shifting towards CIGS, a relatively novel thin film technology that has gained significant attention from stakeholders across the globe. With its efficiency expected to surpass that of CdTe in the next few years and its potential to overcome challenges associated with CdTe and a-Si, the market for CIGS technologies is expected to grow at a relatively higher rate (Research and Markets 2017). Figure 3 shows the trend in growth of thin film technologies.

TFP technologies are currently not as efficient as those of c-Si (Research and Markets 2014) and therefore, more thin film modules are required to

generate the same amount of energy, but they are strongest in the utility scale market because the cost of the panels outweighs the cost of land and labor.

Considering that there is a huge potential for efficiency improvements in TFP technology, this sector could see the growth again with expected production share to exceed 20% of the PV market by 2020 (GBI 2012; U.S. Energy Information Administration 2017).

Towards Sustainable PV

Solar PVs will contribute extensively to satisfy ever-increasing global energy needs. Therefore, issues of sustainability and cost needs to be addressed with increased urgency. The search for sustainable PV materials that combine lower costs, lower toxicity, and effective/efficient energy manufacturing processes is becoming increasingly important. There is a clear need to focus upon the externalities related to the use of PV materials and the evaluation of their impacts.

The PV industry should not just focus upon fabricating high efficiency PV modules, but also focus upon several other issues that are critical for its progress towards large industrial-scale PV production. These issues include: (1) long-term stability; (2) environmentally benign and low-energy manufacturing process; (3) use of abundant, non-toxic materials; and (4) improved disposal/recycle techniques.

Table 2. Global PV market share of TFP technologies (^aWeckend, *et al.* 2016. ^b IEA 2014, ^c Fraunhofer Institute for Solar Energy Systems 2018).

	2000	2005	2010	2011	2012	2013	2014	2015	2016
Global PV cumulative installed capacity (GWs) ^{a,b}	1.3	5.1	40.3	70	100	140	182	242.7	320
Global thin film photovoltaic (TFP) technology production share in PV market ^c									
Percentage (%)	10	5	13.2	13	11.5	9.4	6.8	7.3	6
Gigawatts (MWs)	14	100	2,300	4,200	3,220	3,500	3,615	4,200	4,900
Global CdS-buffered TFP technology market share in PV market									
Percentage (%)	1	1	10	8.5	8	8	6.1	6.6	5.7
Gigawatts (MWs)	1.4	20	1,950	2,900	2,500	2,750	2,875	3,550	4,400
Global cumulative CdS-buffered PV installation, 2000–2016 (MWs)	20,746								

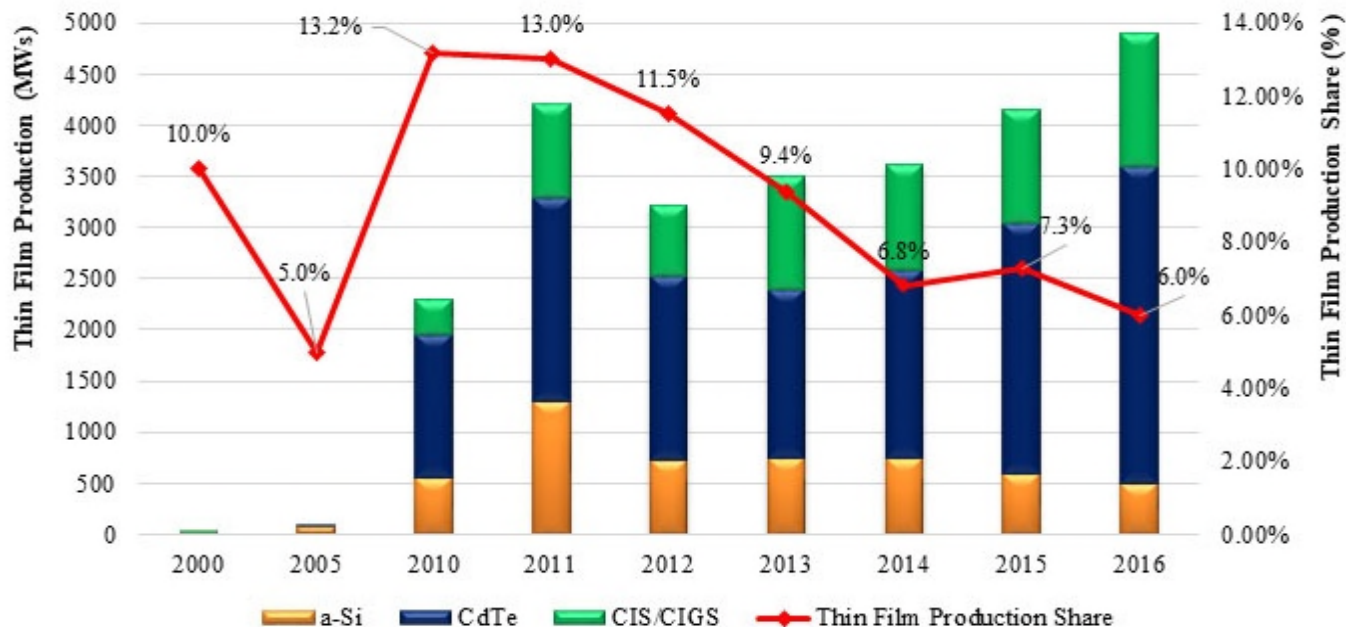


Figure 3. Global thin film PV production.

Assessment and Monetization

Emissions from CdS Buffer Layer

Cd is utilized in two different ways in the process of fabricating PV modules. CdS is used as a buffer layer and CdTe is used as an absorber layer. There are several deposition techniques that are employed in fabricating CdS/CdTe-based PV systems (Green *et al.* 2017; Hultqvist *et al.* 2007; Rusu *et al.* 2005; Gupta and Compaan 2004; Fella *et al.* 2010). Some of these techniques, such as physical vapor deposition (PVD) and atomic layer deposition (ALD), do not possess any significant risk of Cd exposure, whereas techniques such as CBD (on industrial scale) may lead to Cd emissions (Paris and Gmbh 2005). The potential impact upon the environment and human health is from gaseous and aqueous Cd emissions from the CBD process. The synthesis of precursors for CBD is the primary source of Cd emissions to the environment. Indirect Cd emissions are released into the water due to electricity consumed (for heating solution) during the process and for recycling the used bath in the process (Fthenakis and Kim 2007). Figure 4 illustrates the total Cd emissions into the environment from depositing an 80-nm thick CdS film over an area of 1 m² using CBD. The deposition technique in the process emits 6.31 mg of Cd into the air, soil, and water (Philipps *et al.* 2017).

For a 15.7% efficient module of a CdS-buffered PV system, it would require a PV cell area of 6.4 m² to generate a kW of energy on a clear day when solar irradiance for a surface perpendicular to the sun's rays at sea level is about 1000 Watt/m². Therefore, to generate the CdS-buffered PV share (5.7%, 4,400 MW in 2016) in the global TFP market, 28,000,000 m² of film area is required, which could potentially release 176.85 kg of total Cd into the environment from the manufacturing process. Environmentally friendly PV materials and deposition techniques are needed to avoid these toxic emissions. This explains the regulatory and policy concerns about the amount of Cd utilized in PV systems and the efforts to replace CdS with an alternate buffer material.

Manufacturing Costs

The minimum quantified material and energy required to deposit 1 m² CdS (~80 nm thick layers) buffer layer for a CdS-buffered PV system using CBD method is shown in Table. 3 (Raugei and Fthenakis 2010). The associated calculated manufacturing cost of CBD CdS was \$2.80 over an area of 1 m². The prices of the chemicals listed in Table. 3 were for retail customers. These prices may be considerably lower for industrial customers. [All the prices were recorded for Alfa Aesar, a Thermo Fisher Scientific Brand as of

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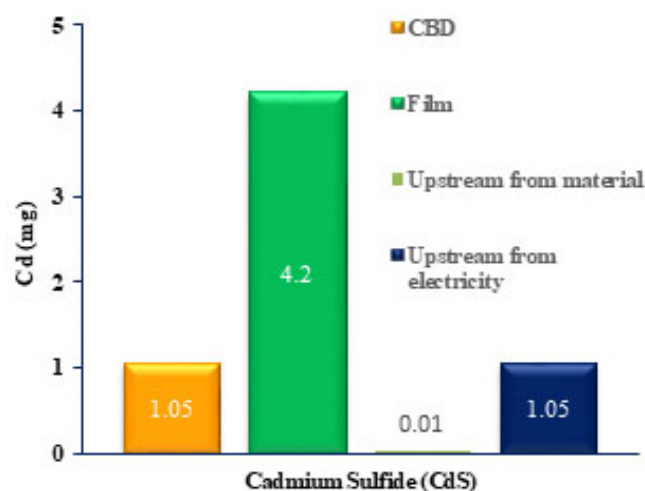


Figure 4. Total Cd Emissions (air, water, soil), from the chemical bath deposition (CD) of a 1-m² CdS thin films, 80 nm thick (Fthenakis and Kim 2007).

December 19, 2018, <https://www.fishersci.com/us/en/home.html>].

Environmental Costs and Issue

In general, the potential environmental impacts associated with solar PV includes land use and habitat loss, use of water and other natural resources, use of hazardous materials, and the life cycle emissions (Hope 2004). The impact varies greatly depending upon the technology type, scale and size of the PV systems, site location, etc. The size of a PV system ranging from small, distributed rooftop PV modules to large utility-scale PV systems will determine the level of environmental impact. Large utility-scale PV systems (range from 3.5 to 10 acres per megawatt) will have higher environmental impact and can raise concerns over land degradation and habitat loss (Edenhofer *et al.* 2011). TFP systems contain a number of toxic materials more than those used in traditional Si-based PV systems. While there are no global warming emissions associated with operation of PV systems (Raugei and Fthenakis 2010), there are emissions associated with other stages of the PV life cycle, including manufacturing, materials transportation, installation, maintenance, and disposal (Hope 2004). Most estimates of life cycle emissions for PV systems are between 0.07 and 0.18 lbs of CO₂E/kWh. This is far less than the life cycle emission rates for natural gas (0.6 - 2 lbs of CO₂E/kWh) and coal (1.4-3.6 lbs of CO₂E/kWh) (IEA 2014). Cd emissions from the life cycle of a PV system are 90-300 times lower than those from coal-powered plants (Hope 2004; Fthenakis 2004).

The environment is exposed to certain amount of Cd naturally through erosion and abrasion of rocks and soils, forest fires, and volcanic eruptions (ICdA 2005). The environmental impact due to Cd emissions from CdS-buffered PV systems during their operation is going to be almost non-existent, since the CdS buffer layer is not only stable, but also encapsulated between other layers with an overlaid glass film (Raugei and Fthenakis 2010; Hope 2004; Fthenakis 2004). First Solar Inc. CdTe technology received various International Electrotechnical Commission (IEC) certifications, and it complies with ISO 9001 and ISO 14001 standards and have a Class B fire rating (Class A Spread of Flame) according to UL and ULC 1703 standards. The glass plates surrounding CdTe material sandwiched between them (as in all commercial modules) seal during a fire and Cd release was negligible (Rix *et al.* 2015). However, a significant portion of scientific community believes that the CdS-based PV modules undergoing serious mechanical damage and chemical changes could cause Cd vapors to escape (Hope 2004; ICdA 2005; European Commission DG ENV 2011), thus harming the environment and life in and around these huge PV arrays. These deadly vapors forced by uncontrolled wind currents might travel to populated areas and cause a catastrophic event. However, end-of-life risks associated with the PV systems are of biggest concern since policies and systems regarding disposal or recycling appear to be inadequate globally (Klugmann-Radziemska 2012). Dollar costs of environmental externalities are difficult to evaluate and depend upon assumptions that can be subject to wide interpretation and discretion. Although, environmental impacts and associated dollar costs are often included in economic comparisons between renewable and conventional energy, investors rarely include such environmental costs in the bottom line used to make decisions.

The environmental problems linked with CdS-buffered PV systems include the release of Cd emissions in air, soil, and water at the manufacturing facility, the installation site and the disposal or recycling facility (Fthenakis 2009). The environmental impacts of Cd emission could result in real cost to society, in terms of human health (loss of workdays, health care costs), infrastructure decay (from acid rain), declines in forests and fisheries, and perhaps ultimately, the costs associated with the climate change (Edenhofer *et al.* 2011). The growing concern about the Cd in the environment is that, if not properly handled after the end-of-life of the PV systems, Cd may escape from landfills and leach into the ground water, contaminating

Table 3. Materials (g) and energy (kWh) required for the chemical bath deposition of 1m² CdS thin films (Raugei and Fthenakis 2010).

Material inputs ^a	Minimum quantity req. (g)	\$ Price (dollars/gram; most quantities are 500g)	Manufacturing cost (\$)
Cadmium sulfate (CdSO ₄)	0.61	4.42	2.69
Thiourea (NH ₂ CSNH ₂)	0.2	0.074	0.02
Ammonia (NH ₄ OH)	1.3	0.03	0.04
Electricity (kWh)	0.4	0.1152	0.05
Total manufacturing cost			2.80

streams, lakes, and rivers, and changing their acidic balance, and putting not just human health, but aquatic organism lives also on risk (Plachy 2003; National Research Council (US) Subcommittee on Zinc Cadmium Sulfide 1997). Furthermore, Cd is bound to particulate matter and can easily be taken up by bottom-dwelling animals as food (National Research Council (US) Subcommittee on Zinc Cadmium Sulfide 1997). According to a study by BIO Intelligent Service, Cd leaching is, on average, at 7% of the volume of Cd contained in a PV module condition to no change in the pH value of the module. However, Cd leaching in landfill settings could potentially increase by 29% if exposed to a lower pH such as nitric acid or acid rain (European Commission DG ENV 2011).

Cd is a major component of CdTe PV modules and a secondary component in CIGS PV module, with approximately 4.60 g and 0.368 g of Cd present in an average CdS-buffered CdTe and CIGS PV module (that weighs about 12 kg/m²). Hence, the potential for Cd leaching into the environment is between 0.03 and 0.32 g per about 12 kg/m². Hence, the potential for Cd leaching into the environment is between 0.03 and 0.32 g per PV module (Fthenakis 2004). The external cost of environmental pollution linked to Cd leakages, respectively, is reported to be \$76,852.2 per U.S. ton (European Commission DG ENV 2011), which means that the environmental cost for the installed CdS-buffered PV capacity (2000-2016) could total \$5.73 million (see Table. 4). However, this cost will vary over time and will decrease with improved technologies to safely dispose/recover Cd. PV systems have a lifetime of 25 years, and considering the last two decades of significant production, the recycling will begin in earnest by 2030 for PV capacity installed in 2005.

Healthcare Costs and Issues

The potential adverse health issues linked with

exposure to Cd are primarily at the PV manufacturing facility and disposal, or recycling facility, whereas Cd emissions are substantially below human health evaluation levels during the life of the PV system (Raugei and Fthenakis 2010).

Cd is considered to be among the most toxic materials used in the PV industry. It is carcinogenic with a biological half-life of 30 years and is known to have long-term effects upon the kidneys (Wennerberg 2002, Butterman and Plachy 2002). Cd could enter and harm the human body through several pathways. It can be ingested through contaminated food and water, but the more potent method could be through inhalation of Cd vapors (National Research Council (US) Subcommittee on Zinc Cadmium Sulfide 1997). Inhaling Cd can cause pneumonitis, pulmonary edema, and death. Intense exposure may lead to more serious effects resulting from severe bronchial and pulmonary irritation. Its effect on liver and kidneys can manifest as various diseases including cancer (Hope 2004). Cd was one of the eleven metals among 53 chemicals on the Persistent Bioaccumulative Toxic (PBT) list targeted by the environmental protection agency (EPA) for a 50% reduction in 2005 (Butterman and Plachy 2002). People who work in PV manufacturing settings, where Cd-containing materials are mostly used in powder form, are at most risk as its dusts can easily be inhaled. Despite Cd exposure well below the threshold limit value (TLV), workers who are involved in the manufacturing process could potentially be at risk for significant exposure, well in excess of the TLV (Spinazzè *et al.* 2015). Persons who survive such acute exposure episodes may recover without permanent damage, but it is possible that repeated episodes of acute or subacute pneumonitis may result in development of lung emphysema. Cd exposure is also believed to cause cancer and high blood pressure (Sinha *et al.* 2014).

The external cost related to human health damage

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from Cd emissions/leaching is approximately \$54,431.6 per U.S. ton (European Commission DG ENV 2011), which means that the cost of human health damage from the installed CdS-buffered PV capacity (2000-2016) could total \$4.1 million (see Table. 4). These costs are based upon not only the improper disposal of Cd from residues from CdTe and CIGS technologies, but also PV modules in ambient use allowing uncontrolled Cd leaching into soil or emissions into air.

Recycling and Disposal Costs and Issues

Recycling and disposal of PV systems is difficult due to the decades-long period between the installations and end-of-life of PV modules, a relatively low concentration of the PV materials, and geographical dispersion (Heath *et al.* 2017; Fthenakis 2000). This requires proper scheduling and sustainable recovery methods. PV waste is expected at two levels: (1) manufacturing; and (2) end-of-life PV module. With recycling to start in significant volume by 2030, the total quantity of disposed PV system waste mostly consists of glass and could total 70.8 million MT globally by 2050 (see Figure. 5). If this waste was fully injected back into the economy, the recovered material could worth more than \$15 billion, thus increasing the efficacy for producing future PV systems or other raw-material-dependent technologies, since costs for material recycling are usually lower than the costs for new technical-grade material. This amount also equates to the raw materials required to synthesize two billion modules and produce 630 GW of energy (Heath 2017), with potential to decrease the energy payback time period to 0.6 - 1.14 years, which is currently between six and eight years (Fthenakis 2009). Thus, economics alone is likely to generate interest in recycling. Companies like First Solar, SunPower, Panasonic, SolarCity, Trina Solar, etc. have already implemented recycling programs, however, these initiatives should be driven by environmental responsibility rather than the economic benefits (Fthenakis 2000). By the end of 2016, 0.25 million MT of PV waste was generated, representing 0.6% of the total mass of the globally installed PV systems, which stands at 4 million MT (Weckend *et al.* 2016). Figure 5 shows the projected PV system waste from the disposed modules, its value creation, and potential to produce PV systems and equivalent energy.

Industrial processes to recycle TFP modules are already established, and can retrieve substances like glass and Al, as well as semiconductor-related materials (Heath *et al.* 2017). The typical composition of a TFP module is: 84% glass, 12% of Al frame, 3% polymer

encapsulant, and the most essential materials forming the PV layers (Mo, Cu, In, Ga, Se, Cd, Zn, S) are only a very small fraction of about 23 g in a 12 kg square meter (1m²) sized module (Klugmann-Radziemska 2012). The mass of recovered semiconductor materials for 1 m² PV module is approximately 5.23 g and 8.62 g for Ga and In, and 8.98 g and 9.15 g for Cd and Te (Klugmann-Radziemska 2012). A number of recycling techniques are under development globally for PV modules. These recycling and treatment options vary by producer and type of technology. However, policy actions are needed to address the global challenges associated with increasing volumes of PV modules waste going forward. Frameworks that enable efficient waste management tailored to the needs of each country or state are essential. China, Germany, and Japan are expected to be the top three countries for solar PV panel waste by 2030. By 2050, China is still expected to have the highest amount of waste. The U.S. will overtake Germany in the second place with Japan expected to remain in third place (Heath *et al.* 2017). EU countries have pioneered electronic waste regulations that cover PV module collection, recovery, and recycling targets. The EU WEEE Directive requires that all solar PV module suppliers finance the end-of-life collection and recycling costs (European Commission DG ENV 2011). In contrast, many countries classify PV modules as either general or industrial waste. In Japan and the U.S., general waste regulations may include testing these modules for hazardous content and prescribing and prohibiting specific shipment, treatment, recycling and disposal methods (Weckend *et al.* 2016). First Solar recycles CIGS and CdTe TFP modules with recovery rates of 90% for glass and 95% for semiconductor materials (Krueger 2009). With the purchase of each First Solar module, funds are set aside to cover the estimated future costs of collection and recycling. These funds pay for all packaging and transportation costs associated with the collection and recycling of the modules. This program follows a three-step process: register each module, collect each module once dismantled, and recycle the modules for material recovery (Krueger 2010). An efficient recycling method can diminish the environmental impacts of manufacturing waste as well as end-of-life module waste, while economically recovering the materials for future use. Ideally, the design and production process of PV components should incorporate the end-of-life dismantling of components into the parts that can be reused or recycled. The manufacturers also have a strong financial incentive to ensure that these highly valuable and often rare materials are recycled rather

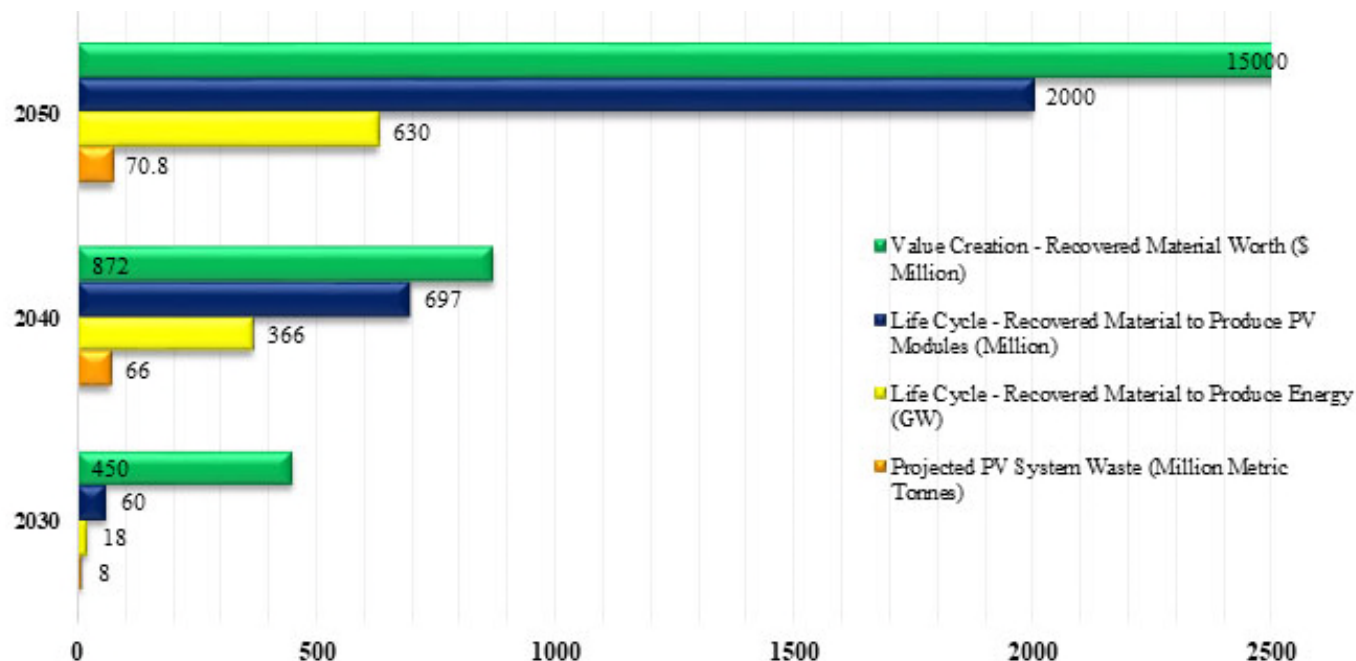


Figure 5. Projected PV system waste from disposed modules; value creation, and potential to produce PV systems and equivalent energy from recovered PV material (Heath *et al.* 2017).

than discarded. The recycling methods and procedures for Cd at present are similar to those for NiCd batteries and LCDs (Fthenakis 2000). Additionally, if all of the aqueous waste containing Cd compounds from rinsing, plate stripping, and ion exchange regeneration can be converted to Cd and Cd salts through precipitation and filtration, the industry could reduce both the manufacturing cost plus Cd emissions into the environment since most of the Cd will be recovered from the waste bath (Fthenakis 2004). A study at Japan Storage Battery Association (JSBA) revealed that the price of the material has an inverse relation with the quantity of recycled materials (Scoullou *et al.* 2001).

The total estimated cost of recycling in TFP modules is approximately 10 ¢/W including transportation and collection costs (Fthenakis 2000). Therefore, the estimated total recycling costs for CdS-systems to incur for capacity installed from 2000 to 2016 could total \$2.08 billion (Table 4). [Estimated Cd content from TFP waste was calculated using following formula: (number of modules required to generate the TFP market share x cadmium content in the module)/(weight of the module (12 kg)). The result was then converted into U.S. tons. Estimated Cd leaching into the environment was calculated using following formula: (number of modules required to generate the TFP market share x potential for Cd leaching into the

environment (0.32 g/module). The result was then converted into U.S. tons. Estimated Cd emissions from the manufacturing process was calculated using following formula: (number of modules required to generate the TFP market share x Cd emissions from CBD of CdS thin film (6.31 mg/m²)).

Safe disposals of various components of TFP module suggests the decommissioning of the modules should be done in a way that no hazardous material is released into the environment. If the toxic material ends up in landfills, it could leach into the ground water, or in incinerators, burning materials resulting in emission of toxic to the air (Sinha *et al.* 2014; Weckend *et al.* 2016). Although the cost of landfill disposal of PV modules is still lower than the cost of recycling the modules (European Commission DG ENV 2011), recycling is environmentally profitable. Additionally, with improved recovery methods, recycling costs are expected to decrease, whereas the landfill disposal costs are constantly increasing due to increased environmental regulations associated with the disposal of hazardous material to protect the environment (T. E. P. A. T. C. O. and European Union 2003). The cost of landfill disposal is 1 ¢/W for large quantities of non-hazardous waste and 23 ¢/W for hazardous waste excluding packaging and transportation costs, respectively (Fthenakis 2000). Therefore, the estimated total disposal

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Table 4. Monetization: External costs related to use of Cd in CdS-buffered System.

Cadmium-containing TFP technology market share (MWs) by type:		
Year of production (Philipps <i>et al</i> 2018)	CdTe	CIS/CIGS
2000	-	1
2005	20	-
2010	1,400	350
2011	2,000	900
2012	1,800	700
2013	1,650	1,100
2014	1,850	1,025
2015	2,450	1,100
2016	3,100	1,300
Total TFP market share in the PV market (MWs)	14,270	6,475
	20,745	
Number of modules (100 watt) required to generate the market share	1,712,400,000	777,000,000
Estimated cadmium content present in TFP Waste (in U.S. tons) (Fthenakis 2004)	723	23
Environmental Costs		
Estimated Cd leaching into the environment (in U.S. tons) (Fthenakis 2004)	50	23
Estimated Cd emissions from manufacturing process (U.S. tons)	1	0.45
Estimated total environmental costs (in million dollars) @ \$76,852.2/U.S. ton of Cd leaching (European Commission DG ENV 2011)	5.73	
Healthcare Costs		
Estimated total human health damage costs (in million dollars) @\$54,431.6/U.S. ton of Cd leaching (European Commission DG ENV 2011)	4.1	
Recycling and Disposal Costs		
Estimated Recycling Costs (10¢/watt) in billion dollars (Fthenakis 2000)	2.08	
Estimated Disposal Costs (23¢/watt) in billion dollars (Fthenakis 2000)	4.77	

costs for CdS- buffered PV systems to incur for capacity installed from 2000 to 2016 could total \$4.77 billion. Due to uncertainty and limited information on the extent of the future recycling and disposal costs from potential technological shifts, we used fixed rate while calculating these costs based upon prices available in the literature.

Conclusion

The impact of any new technological advance/

material upon human health and the environment must be carefully examined before it can be adopted on a large scale. Issues of sustainability and cost needs to be addressed with increased urgency, and there is a clear need to focus upon the externalities related to the use of PV materials and the evaluation of their impacts. CdS-buffered TFP technology has now matured and it is now important to assess its impact before it is widely adopted. The external costs related to environment, human-health damages, and disposal from use of Cd will outweigh the high price of other alternate PV

materials. These external costs will exponentially increase as demand for energy increases in the future.

If researchers from diverse scientific disciplines can work together with support from manufacturers and monitoring by governmental agencies, nearly any technology can be utilized in a smart and profitable manner with minimal-to-no harm to the humans, thus, avoiding socio-economic burdens. If government, industry, and research institutions each play their respective parts, the potential payoff is significant, given recycling PV modules is expected to represent a \$15 billion opportunity worldwide by 2050. Potential environmental impacts of minimizing Cd leaching and resource loss due to non-recovery of valuable conventional resources and rare metals in PV modules are significant. Until these issues are properly addressed, a shadow of doubt will hang over the true environmental impacts of solar energy.

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