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

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Abstract: As the world's population continues to grow, global energy crises are expected to rise in the future, thus accelerating the demand for renewable energy technology, particularly solar photovoltaics. The energy sector will face an increasingly complex array of interlocking challenges - technological, environmental, health, economic, and regulatory. In this paper, we study CdS, a widely used buffer material in thin film photovoltaics, to assess and monetize environmental, health, and socio-economic externalities associated with the use of the material. Currently, CdS has a significant advantage over other alternate buffer materials in terms of efficiency and low-cost production of large-area processing of thin films, but the potential environmental risks associated with the use of cadmium are of concern. 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 photovoltaic technologies.

Key words: cadmium sulfide, thin film photovoltaics, environment, health, socioeconomics

1. Introduction

Solar photovoltaics (PV) convert 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 pn junction with the absorber layer and allowing maximum transmission of light (minimum absorption loss) to the junction region and the absorber layer. Buffer layers passivate the junction material, providing a layer of appropriate thickness and index of refraction that reduce the overall reflectance, while avoiding shunts between the absorber and the front electrode [1, 2].

Fig. 1 illustrates the solar cell structure that utilizes n-type cadmium sulfide (CdS) and p-type cadmium telluride (CdTe) as an example buffer and absorber materials. The buffer layer is sandwiched between the absorber layer and 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 PV cell [3, 4]. The absorber layer constitutes the core of any PV device; however, the junction interface properties between the absorber and buffer layers have proven to be significant to the performance of the device [5]. Therefore, the buffer

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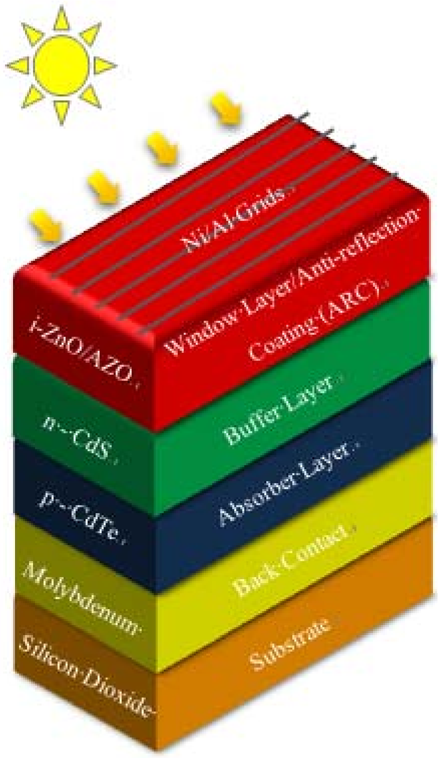

Fig. 1 n-CdS/p-CdTe PV cell structure.

layer is critical to forming a reliable pn junction and establishing good interface properties.

The oldest and the most widely known buffer material is cadmium sulfide (CdS), initially used in solar cells for aerospace applications back in the 1950's [6]. CdS is an important n-type semiconductor material with an optical bandgap of 2.42 eV [7]. The commercially available cadmium telluride (CdTe) and copper indium gallium diselenide/copper indium diselenide (CI(G)S) technologies utilize CdS buffer layer to form a heterojunction interface [8]. Chemical bath deposited (CBD) CdS-based PV devices have yielded good performances, however, there are drawbacks concerning industrial-upscaling from use of the carcinogen thiourea and hazardous Cd in large amounts [9]. CBD encompasses a variety of routes for synthesizing thin films at a relatively low temperature by immersing a substrate in a liquid solution [10]. The process involves generation of S^{-2} 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 [1]. Other depositions techniques such as atomic layer deposition (ALD) and sputtering exist for depositing thin CdS films, however, these techniques are expensive comparatively to the CBD. Several studies have emphasized upon the replacement of CdS in chalcopyrite PV devices due its toxicity [5, 7, 9]. However, the PV industry is reluctant to replace CdS, as it is a proven material which reached energy conversion efficiencies of 23.3% for a 0.5 cm^2 laboratory cell in 2016 [11]. Although research is underway to evaluate alternatives for CdS, the most efficient heterojunction PV devices utilize a CdS buffer layer [12]. Table 1 summarizes the operational performance of record CdS-buffered thin film photovoltaics (TFP) devices synthesized by different deposition techniques.

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) [17]	16.7	32.8	671	75.8	0.5
Chemical Bath Deposition (CBD) [11]	23.3	32.98	621	74.7	0.5
Physical Vapor Deposition (PVD) [18]	14.1	31.4	610	73	0.5
Sputtering [19]	14	23.6	814	73.25	0.3
Ultrasonic Spray Pyrolysis (USP) [20]	12.5	30.3	570	73	0.3

Cadmium (Cd) compounds (CdTe, CdS, etc.) are widely used in PV devices. These compounds are highly toxic [13], and 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, and therefore, human exposure to these hazardous chemicals by inhalation, ingestion, or skin contact poses a great risk to human health and social conditions [14]. The toxicity of Cd came to light with the outbreak of "itai-itai" disease in Japan in 1950's [15]. 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 [16]. Since then there has been gradual increase in awareness regarding adverse impacts of Cd to human health.

In 1993, the International Agency for Research on Cancer (IARC) classified Cd as a Category 1 human carcinogen [21]. Later, the National Toxicology Program (NTP) conducted their independent assessment and concluded that Cd and Cd-compounds are human carcinogens [22]. 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 secure energy is the main enabler for the welfare and economic development of a society. Due to the rapid solar PV growth in the last two decades, it is indispensable to provide an energy system which covers the needs of the economies and preserves the environment, as well as presenting no adverse effects to human health. In this paper, the objectives were threefold: (1) investigate emissions from CBD CdS buffer layers and during the life cycle of PV cells, and their potential for release into the environment; (2) examining potential environmental and health risks related to manufacturing and disposal; and, (3) asses and monetize environmental, health, and socio-economic externalities associated with CdS-buffered PV systems using the economic data in the literature on the effects of environmental changes on human health from use of hazardous materials.

2. Global Photovoltaic 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) [23]. Meaning, 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 reserves of fossil fuels corresponds to only 20 days of sun shine [24]. In the economic world, we have already wasted a huge amount of energy and we must harness this energy resource efficiently. PV production has increased dramatically since 2005 in the United States (U.S.), reaching 40 gigawatts (GW) of installed PV capacity in 2016 from five gigawatts (GW) in 2005, with global installed capacity reaching 303 GW [25]. According to the International Energy Agency's (IEA) Technology Roadmap on Solar Photovoltaic Energy (2014 Edition), the PV share in global electricity production could reach 16% by the end of 2050 with installed PV capacity reaching 4,512 GW (or 4.512 TW), since the world's energy growth in consumption is expected to reach 33 terawatts (TWy) [26]. The global projection for cumulative PV installed capacity, and market growth rate and share by region can be seen in Figs. 2 and 3.

Photovoltaics is the fastest growing market with compound annual growth rate (CAGR) of PV installations of 40% between 2010 and 2016 [27]. In 2016, Europe's contribution to the cumulative PV installations amounted to 33% compare to 26% for China and Taiwan [25], 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%. By 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 [28].

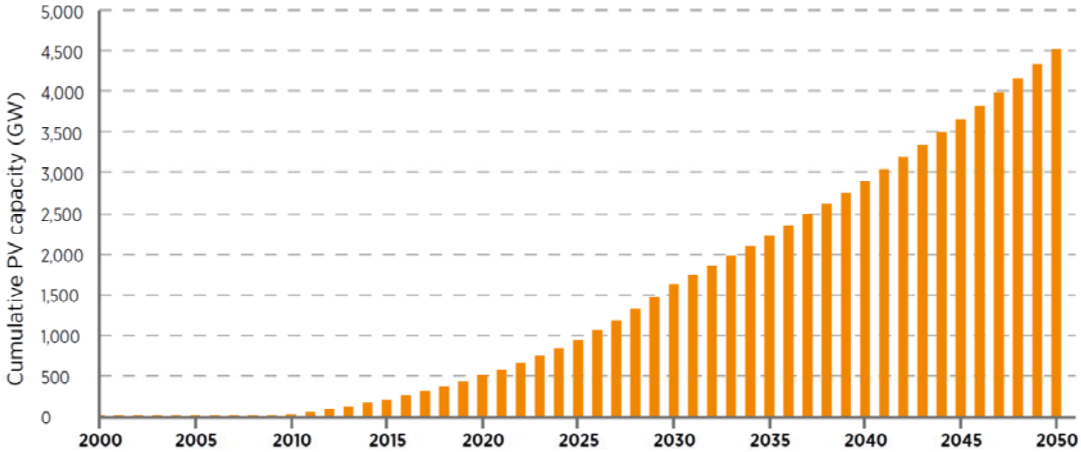

Fig. 2 Projected cumulative global PV installed capacity, 2000-2050 (Source: International Renewable Energy Agency (IRENA, 2014)).

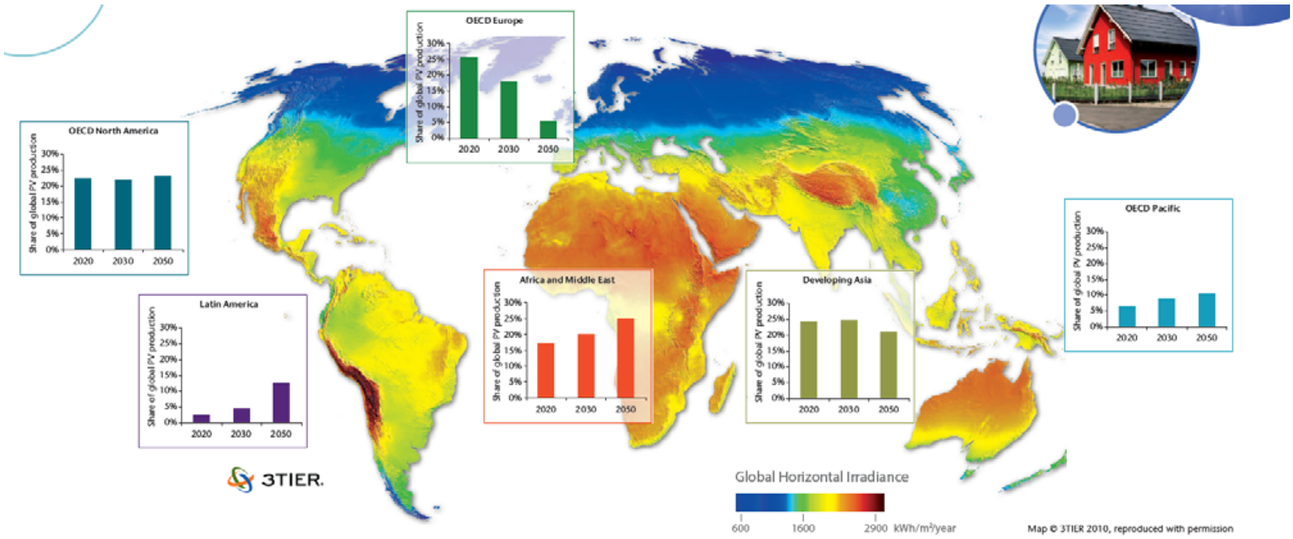

Fig. 3 Global projections for cumulative PV installed capacity by region, 2010-2050 (Source: International Energy Agency (IEA, 2014).

TFP technologies are subdivided into three main families: (1) amorphous (a-Si) and micromorph silicon (a-Si/μc-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 [25, 27], see the timeline of global PV market share of TFP technologies from 2000 to 2016 in Fig. 4), which also reflects the challenges faced by the 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 CI(G)S technologies is respectively 3.9% (3,100 MWs) and 1.8% (1,300 MWs) [25, 27] in which CdS is deployed as a buffer material [29]. Global PV cumulative installed capacity reached 320 GWs in 2016 with cumulative CdS-buffered PV systems installation between 2000 and 2016 equaling 20,746 MWs (see Table 2). Considering that there is a huge potential for efficiency improvements in TFP technology that could see it rise again with expected production share to exceed 20% in the PV market by 2020 [29, 30].

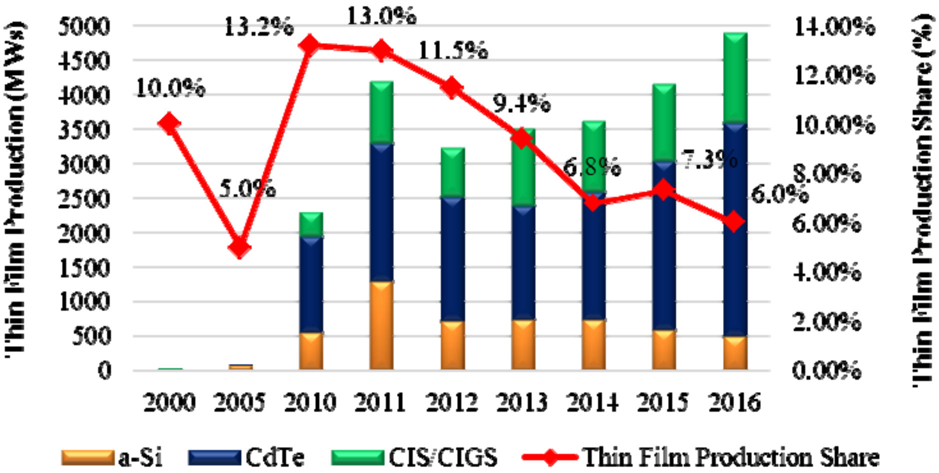

Fig. 4 Global thin film photovoltaic production.

Table 2 Global PV market share of TFP technologies.

	2000	2005	2010	2011	2012	2013	2014	2015	2016
Global photovoltaic (PV) cumulative installed capacity (GWs) [26, 52]	1.3	5.1	40.3	70	100	140	182	242.7	320
Global thin film photovoltaic (TFP) technology production share in PV market [27]									
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								

First Solar has a market share of approximately 90% in CdTe technology, with the majority of market share in North America as the usage of Cd in the European Union (EU) countries highly regulated. Hanergy Thin Film Power has one-third of the market share of CI(G)S technology and a majority of its share is in the Asia-Pacific and European markets [31].

Initially, amorphous silicon's (a-Si) share had rapidly increased due to reduced costs as Chinese manufacturers became strong in the technology [32]; however, the focus is gradually shifting towards CI(G)S, 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 CI(G)S technologies is expected to grow at a relatively higher rate [33], also evident from Fig. 4. TFP technologies are currently not as efficient as those of c-Si [31] and therefore, more thin film modules are required to generate the same amount of energy, it is strongest in the utility scale market because the cost of the panels outweighs the cost of land and labor. Hence, the TFP share is projected to rise exponentially in the future.

3. Towards Sustainable Photovoltaics

Solar PV 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 efficient PV modules, but also focus upon several other issues that need to be considered as sensitive areas of research and development to progress towards large industrial-scale PV production. These issues include: (1) long-term stability; (2) environmentally benign and low-energy manufacturing processes; (3) use of abundant, non-toxic materials; and (4) improved disposal/recycle techniques.

4. Assessment and Monetization

4.1 Emissions from CdS Buffer Layer

Cd can be 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 [11, 17-20]. 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 other techniques such as CBD industrially utilized may lead to Cd emissions [9]. 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 [34]. Fig. 5 illustrates the total Cd emissions into the environment from depositing an 80-nm thick CdS film over an area of 1m^2 using CBD. The deposition technique in the process emits 6.31 mg of Cd into the air, soil, and water [25].

In CdS–buffered PV systems, for a module that is 15.7% efficient, 6.4 m^2 of PV cell area is required 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/m^2. Therefore, to

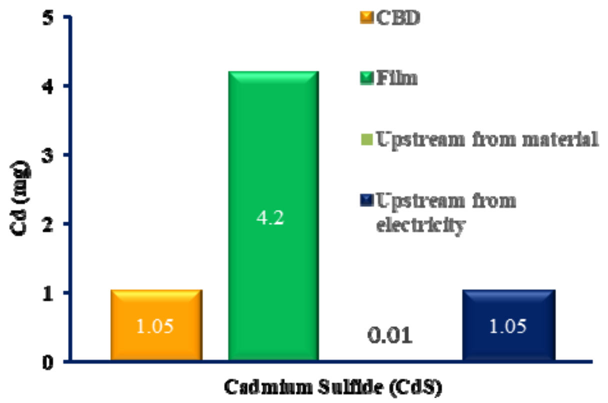

Fig. 5 Total Cd emissions (air, water, soil), from the chemical bath deposition (CBD) of a 1-m^2 CdS thin films, 80 nm thick [34].

generate the CdS-buffered PV share (5.7%, 4,400 MW in 2016) in the global TFP market, 28,025,477.71 m^2 of film area is required, which could potentially release 176.85 kg of total Cd into the environment from the manufacturing process. Hence, we require environmentally friendly PV materials and appropriate deposition techniques to avoid polluting the environment, and therefore, regulatory and policy concerns about the amount of Cd utilized in PV systems are driving efforts to replace CdS with an alternate buffer material.

4.2 Manufacturing Costs

To fabricate CdS-buffered PV systems, the minimum quantified material and energy required to deposit 1 m^2 CdS buffer layer using CBD method is demonstrated in Table 3 [35], which summarizes the list of materials for the synthesis of CdS buffer layer and the energy required for depositing ~80 nm thick layers. The associated calculated manufacturing cost of CBD CdS is \$2.80 over an area of 1 m^2. The prices of the chemicals listed in Table 3 are for retail customers. These prices may be considerably lower for industrial customers.

4.3 Environmental Costs and Issues

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 [36]. 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 [37]. TFP systems contain a number of more toxic materials than those used in traditional Si-based PV systems. While there are no global warming emissions associated with operation of PV systems [35], there are emissions associated with other stages of the PV life cycle, including manufacturing, materials transportation, installation, maintenance, and disposal [36]. 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 CO_2 E/kWh) [26]. Cd emissions from the life cycle of a PV system are 90-300 times lower than those from coal-powered plants [36, 38].

Table 3 Materials (g) and energy (kWh) required for the chemical bath deposition (CBD) of 1m^2 CdS thin films.

Material inputs [35]	Minimum quantity req. (g)	$ Price (dollars/gram; most quantities are 500 g)	Manufacturing cost ($)
Cadmium sulfate ($CdSO_4$)	0.61	4.42	2.69
Thiourea (NH_2CSNH_2)	0.2	0.074	0.02
Ammonia (NH_4OH)	1.3	0.03	0.04
Electricity (kWh)	0.4	0.1152	0.05
Total manufacturing cost			**2.80**

*All the prices of chemicals were recorded for Alfa Aesar, a Thermo Fisher Scientific Brand as of December 19, 2017, available online at: https://www.fishersci.com/us/en/home.html.

The environment is also exposed to Cd naturally through erosion and abrasion of rocks and soils, forest fires, and volcanic eruptions. Some Cd levels occurring through natural resources in the environment are listed below [39]:

Atmosphere	0.1 to 5.0 ng/m^3
Earth's crust	0.1 to 0.5 µg/g
Marine sediments	1 µg/g
Sea water	0.1 µg/L

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 [35, 36, 38]. First Solar CdTe technology received various International Electrotechnical Commission (IEC) certifications, comply 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 [40]. However, a significant portion of scientific community believes that the CdS-based PV modules undergoing serious mechanical and chemical changes could cause Cd vapors to escape [36, 39, 41], thus destroying 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. 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 [37]. End-of-life risks associated with the PV systems are the biggest concern since policies and systems regarding disposal or recycling appear to be inadequate globally [42]. 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 [43]. If not properly disposed, it can cause Cd leaching, loss of conventional resources (aluminum and glass), loss of relatively rare metals (Ag, In, Ge, Ga, Te, Se). 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 [44]. Cd is a major principle material in CdTe PV modules and a secondary component in CI(G)S PV module, therefore, approximately 4.60 g and 0.368 g of Cd is present in an average CdS-buffered CdTe and CI(G)S PV module (that weighs about 12 kg/m^2). Hence, the potential for Cd leaching into the environment is between 0.03 and 0.32 g per PV module [38]. The external cost of environmental pollution linked to Cd leakages, respectively, is reported to be $76,852.2 per U.S. ton [44], 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 start in earnest by 2030 for PV capacity installed in 2005.

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 streams, lakes, and rivers, and changing their acidic balance, and putting not just human-health, but aquatic organism lives also on risk [45, 46]. Furthermore, Cd is bound to particulate matter and can easily be taken up by bottom-dwelling animals as food [46].

4.4 Healthcare Costs and Issues

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. 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 [35].

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 [2, 47]. 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 [46]. Inhaling Cd can cause pneumonitis, pulmonary edema, and death. Intense exposure may lead to more serious effects resulting from severe bronchial and pulmonary irritation. Death may result primarily in the liver and kidneys and manifesting as various diseases including cancer [36]. 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 by 2005 [47].

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

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 [27]	**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) [38][1]	723	23
Environmental Costs		
Estimated Cd leaching into the environment (in U.S. tons) [38][2]	50	23
Estimated Cd emissions from manufacturing process (U.S. tons)[3]	1	0.45
Estimated total environmental costs (in million dollars) @ $76,852.2/U.S. ton of Cd leaching [44]	5.73	
Healthcare Costs		
Estimated total human health damage costs (in million dollars) @$54,431.6/U.S. ton of Cd leaching [41, 44]	4.1	
Recycling and Disposal Costs		
Estimated Recycling Costs (10¢/watt) in billion dollars [51]	2.08	
Estimated Disposal Costs (23¢/watt) in billion dollars [51]	4.77	

1. 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.
2. 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.
3. 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/m^2)).

manufacturing process could potentially be at risk for significant exposure, well in excess of the TLV [48]. 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 favor the development of lung emphysema. The effects of widespread Cd exposure are still unknown, but are thought to be cancer and high blood pressure [49].

The potential for Cd leaching from landfills into the environment is estimated between 27 g and 153 g per ton of PV module, based upon current estimates of Cd quantities in PV modules [44]. However, it should be noted that these quantities could reduce in the future. The external cost related to human health damage from Cd emissions/leaching is approximately $54,431.6 per U.S. ton [41], which means that the cost of human health damage from the installed CdS-buffered PV capacity (2000-2016) could total $4.1 million (see Tab. 4). These costs are based upon not only the improper disposal of Cd from residues from CdTe and CI(G)S technologies, but also PV modules in ambient use allowing uncontrolled Cd leaching into soil or emissions into air.

4.5 Recycling and Disposal Costs and Issues

Recycling and disposal of PV systems will be 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 [50, 51]. 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 consist of glass and could total 70.8 million MT globally by 2050 (see Fig. 6). 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 [50], with potential to decrease the energy payback time period to 0.6-1.14 years, which is currently between six and eight years [42]. Thus, economics alone is likely to generate interest in recycling. Companies like First Solar, SunPower, Panasonic, SolarCity, Trina Solar, etc. [51] have already implemented recycling programs, however, these initiatives should be driven by environmental responsibility rather than the economic benefits. 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 [52].

See Fig. 6 for projected PV system waste from the disposed modules, its value creation, and potential to produce PV systems and equivalent energy.

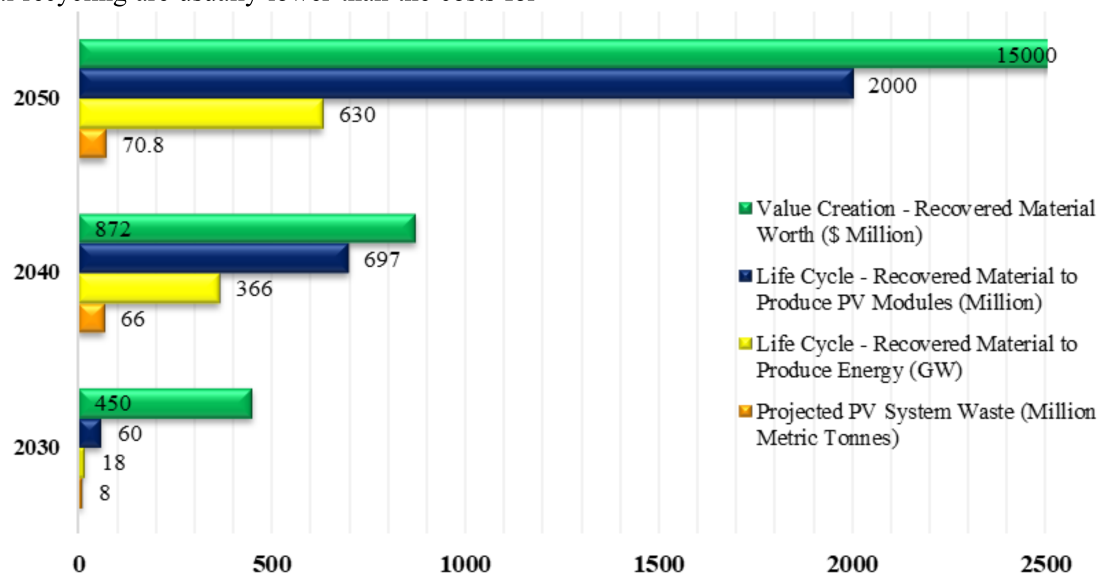

Fig. 6 Projected PV system waste from disposed modules; value creation, and potential to produce PV systems and equivalent energy from recovered PV material [50].

Industrial processes to recycle TFP modules are already established, and can retrieve substances like glass and Al, as well as semiconductor-related materials [50]. 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 (1 m^2) sized module [42]. The mass of recovered semiconductor materials for 1 m^2 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 [42]. 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 action is 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 [50]. 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 [41]. 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 [52]. First Solar recycles CI(G)S and CdTe TFP modules with recovery rates of 90% for glass and 95% for semiconductor materials [53]. 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 system: register each module, collect each module once dismantled, and recycle the modules for material recovery [54]. An efficient recycling method can reduce the environmental impacts of manufacturing waste as well as end-of-life module waste, while economically recovering the materials for future use. To obtain an environmental benefit, the impact related to the recycling process has to be lower than that related to the production of the replaced PV material. It must be mandated that in future the design and production of PV components facilitates the end-of-life dismantling of components into the parts that can be reused or recycled. However, manufacturers have a strong financial incentive to ensure that these highly valuable and often rare materials are recycled rather than discarded. The recycling methods and procedures for Cd are far more mature and developed than those for In, and similar to those for NiCd batteries and LCDs [51]. 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 [38]. 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 [55].

We noted that recycling costs vary worldwide; the total estimated cost of recycling in TFP modules is approximately 10 ¢/W including transportation and collection costs [51]. Therefore, the estimated total recycling costs for CdS-systems to incur for capacity installed from 2000 to 2016 could total $2.08 billion (see Table 4).

Safe disposals of various components of TFP module suggests the decommissioning of the modules 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 [49, 52]. Although the cost of landfill disposal of PV modules is still lower than the cost of recycling the modules [44], recycling is environmentally profitable. In addition, it is noted that 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 [13]. 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 [51]. Therefore, the estimated total disposal 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.

5. Conclusion

It is imperative to assess and monetize to evaluate in a quantitative way the environmental, social and economic impacts of any new technology before it is adopted. 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.

Before launching any new technology, it is very important to investigate its impact upon the environment, human-health, and the economy, both short-term and long-term, from a broad perspective. If researchers from diverse scientific disciplines can jointly 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. Limiting the quantity of end-of-life PV modules has the positive environmental impacts of minimizing Cd leaching and potential resource loss due to non-recovery of valuable conventional resources and rare metals in PV modules. Until these issues are properly addressed, a shadow of doubt will hang over the true environmental impacts of solar energy.

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