Collection: Sustainability

Report on

STUDY OF THE ENVIRONMENTAL, HEALTH AND SAFETY OF Cadmium Telluride (CdTe) PHOTOVOLTAIC TECHNOLOGY

By

Prof. Viresh Dutta (PI)
Photovoltaic laboratory
Centre for Energy Studies
Indian Institute of Technology Delhi

Dr. K.Vamsi Krishna (Co-PI)
Centre for Energy Studies
Indian Institute of Technology Delhi

Prof. T.R. Sreekrishnan (Co-PI)
Head
Dept. of Biochemical Engineering
Indian Institute of Technology Delhi

Prof. Udai P. Singh (Co-PI)
School of Electronics Engineering
KIIT University, PATIA, Bhubaneswar

July 2012

First Solar has sponsored a project "**STUDY OF THE ENVIRONMENTAL, HEALTH AND SAFETY OF Cadmium Telluride (CdTe) PHOTOVOLTAIC TECHNOLOGY"** which is being executed in IIT Delhi under the Foundation for Innovation and Technology Transfer (FITT). Apart from the faculty colleagues in IIT Delhi, we have Prof. U.P.Singh, Kalinga Institute of Industrial Technology as Co-PI in the project. The project undertaken by us has two main questions to be probed:

(i) Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product (including recycling)?

(ii) What are the overall life cycle impacts of the large-scale deployment of CdTe PV systems on the environment, public health, and public safety, taking into account other energy alternatives?

The main objective of the project is to study the existing literature on the materials involved in CdTe manufacturing, deployment and end of life situation. Then the understanding of these materials affecting the environment and health in India has to be brought out by comparison with the existing issues of Cd and other heavy metals from other industry getting incorporated in water and/or food chain. Since this can be detrimental to people and can give rise to major health problems, the study throws light on the effect CdTe Photovoltaics may have in this direction.

The report outlines our understanding of the current scenario and is mainly based on the reported literature and reports made available by First Solar. Other reported literature have also been compiled and used to create a holistic perspective on the entire issue and to address to the questions raised by First Solar under the project.

Date: July 31, 2012 (Viresh Dutta)

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Preamble

A study was undertaken, at the behest of First Solar, the largest manufacturer of Cadmium Telluride thin-film based photovoltaic panels, to assess the environmental, health, and safety (EHS) of the production, use, and final disposal of CdTe PV panels, with special emphasis on the Indian scenario.

Methodology

The methodology adopted for this study drew inputs from the following sources:

- Published literature on CdTe PV modules/panels
- Unpublished, but author authenticated literature (reports) on CdTe PV panels, provided by First Solar
- Information gathered through the plant visit undertaken to First Solar's CdTe panel manufacturing and recycling facility located in Malaysia on 21st and 22nd May, 2012
- Conclusions drawn from information provided by First Solar Personnel during the discussions that took place in Malaysian visit.

Observations and Conclusions

Harnessing solar power to meet the ever-increasing demand for power all across the world is a very attractive option, especially so due to its minimal or non-existent air, water and soil pollution. In addition, during operation it does not contribute to greenhouse gas emissions and the global warming phenomenon. While these benefits are accepted and understood by all, translating what is theoretically possible into a large (global) scale operating system needs considerable developmental inputs.

CdTe technology is a late entrant to the market of PV solar power panels. Apparently, this has been mostly due to the lack of technical know-how in translating laboratory findings to a commercially viable option. These obstacles have been overcome by current CdTe PV manufacturer, First Solar. The other, existing, technology based on silicon has so far dominated the market. First Solar has developed the technology for large scale production of CdTe PV modules with energy output comparable to that obtained using silicon modules, and with better performance in diffuse light and high temperature conditions.

Raw material

Cadmium, a heavy metal, is highly toxic. Therefore, any use of Cd compounds has to be weighed against the possible Cd proliferation in the environment as well as exposure of Cd compounds to the personnel involved in the production, use and (safe) disposal of these PV panels. However, CdTe differs from elemental Cd and other Cd compounds (e.g., $CdCl_2$) due to strong bonding that leads to an extremely high chemical and thermal stability [1-3]. CdTe exhibits aqueous solubility and bioavailability properties that are approximately two orders of magnitude lower than the 100% solubility and bioavailability of $CdCl_2$, which means that CdTe does not readily release the reactive ionic form of Cd (Cd^{2+}) upon contact with water or biological fluids. Based on these results, the toxicity and environmental mobility of CdTe would be expected to be much lower than other forms of Cd. The acute inhalation and oral toxicity of CdTe are orders of magnitude lower than that of Cd, and there are no detectable effects of CdTe on male or female rat reproduction [3].

Cadmium is a by-product of the zinc (Zn) production process [4]. Zinc smelters invariably produce Cd-containing sludge and recovery and purification of Cd available from these sludges is more than the global demand for Cd at present. Therefore, production of Cd in itself is not a matter of concern, unless one is in favour of eliminating Zn smelting altogether. Use of Cd in CdTe PV represents a minor (~1%) fraction of the global demand for primary cadmium [31].

Manufacturing

Minor Cd emissions to air and water (within regulatory permissible levels) occur during PV panel production, and are managed with air emissions controls and on-site wastewater treatment. But if we consider the energy produced (from sunlight) by one PV panel and compare it to energy production through fossil fuel burning, we find two major points in support of PV modules: (i) PV panels when in use do not emit GHGs whereas fossil fuels do and (ii) coal and oil, which are commonly used fossil fuels for power generation, also contain heavy metals including Cd (Fig. 1). During combustion, this Cd does get emitted to the air. In addition for coal, heavy metals also get partitioned into the fly ash and pose a grave threat of metal (Cd) proliferation unless the final disposal of the fly ash is done judiciously. In summary, there is a ~89-98% reduction in the emissions of greenhouse gases, and reduction of other heavy metals like cadmium into the environment from the CdTe PV technologies compared to the fossil-fuel based power sources [5].

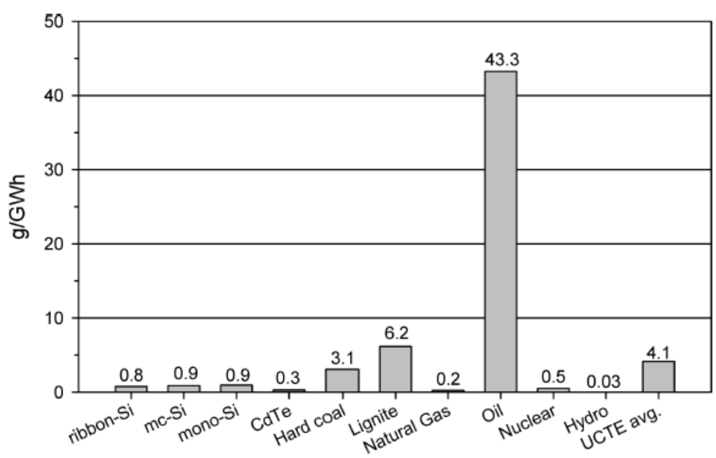

Figure 1. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption in comparison with other electricity generation options [5].

The safety norms in place at the First Solar manufacturing facility is one of the best in the PV industry, for normal industrial safety requirements as well as for tackling the problem of handling the toxic Cd compounds used in the manufacturing operation.

The personnel are provided with appropriate personal protective equipment (PPE) for their work stations and PPE use is strictly monitored for complete compliance. Blood and urine samples of all the personnel who have a possibility for Cd exposure are taken on a regular basis and analysed for their Cd content. The compiled data for almost 10 years, which was made available, shows that the mean Cd level in the blood as well as urine of all the test groups show no evidence of increased Cd exposure from the workplace.

In order to eliminate Cd compounds emitted from specific process equipment from entering the indoor air of the factory, there is in place an elaborate system of air filters. Before entering into the factory, the Cd-contaminated air is made to pass through specially designed filter modules fitted with HEPA filters. The filtered air is then re-circulated into the factory. Air sample data from First Solar manufacturing facilities confirm that indoor air quality at the factory is better than the background (outside air from the particular locality), supporting the effectiveness of the air filtration system.

Product Use

The question more relevant to a user of the PV panel will be the Cd emission during its routine use as well as during a non-routine event such as a fire incident. Almost every literature supports the claim that there is no concern of Cd emission from these panels during their routine installation and operation phases. What could still be of some concern is the fate of Cd in case of a fire incident. CdTe volatilises at temperatures above 1050^{o}C. Such temperatures are possible in case of major fires. A very focused and specially designed experiment to look at the fate of Cd in case of a major fire conclusively proves that the glass panels, which sandwiches the CdTe and CdS layers, melt first and form a complex with the Cd salts, thereby preventing the Cd from volatilising and getting transported through the air (Fig. 2). This study, conducted at a reputed US National Laboratory, conclusively puts to rest the fear of Cd exposure due to fires [6]. Even under extreme situations, the models show that even if all the Cd compound was to be released, Cd concentrations within the near vicinity to the CdTe PV system are below human health screening levels [7, 22, 30].

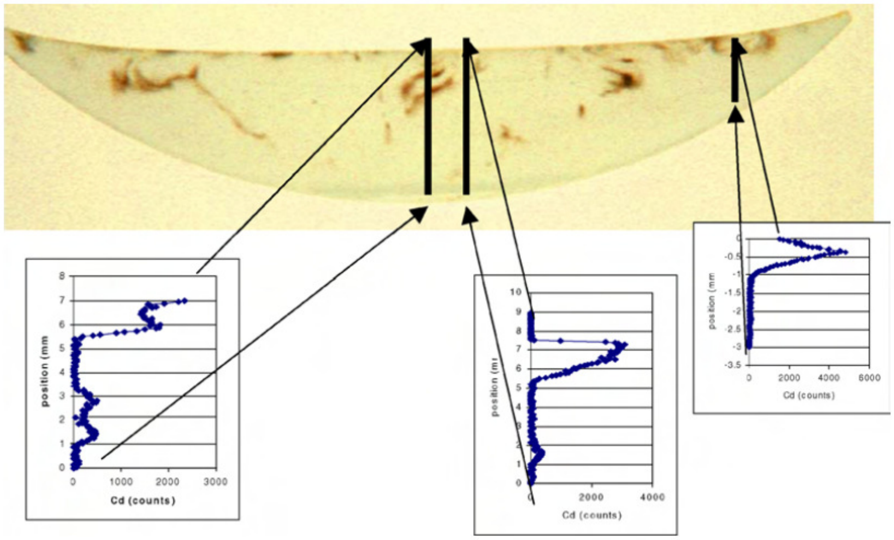

Figure 2. X-ray fluorescence microprobe analysis-vertical slice from middle of sample heated at 1100˚C; Cd counts in the center and the sides of the slice [6].

End-of-Life

Another question that comes to the mind of a potential CdTe PV panel user is, what to do with the CdTe -containing panels once they run out of their productive lives? First Solar warranties a 25 year life for the panels. Once the panels have come to the end of their useful lives and removed from their arrays, they will need to be properly disposed or recycled. In Europe, the end-of-life modules are classified as 'non-hazardous waste' consistent with the EU Waste Framework Directive and the EU Waste Catalogue and are suitable for disposal in 'non-hazardous waste' landfills. Under India's Hazardous Waste Rules, the end-of-life- modules would be classified as non-hazardous waste even though they contain cadmium compounds. The Hazardous Waste Rules have adopted the use of the Toxicity Characteristic Leaching Procedure (TCLP) test (ASTM version) for determining the concentration of hazardous constituents (i.e., cadmium). The concentration of cadmium compounds in the end-of-life CdTe modules are below the threshold of concern. In addition, according to the Indian Landfill Act, a landfill can be either 'inert' (no biodegradables) or 'hazardous' (containing at least any one component classified as hazardous). So even though the CdTe PV panels would be classified as non-hazardous waste and could be disposed of in a municipal waste landfill, they may have to be disposed of in a hazardous waste landfill because of the perception that the panels are a form of electronic waste. Starting and operating a hazardous waste landfill is an extremely difficult task in India at present, mostly due to socio-economic factors.

First Solar currently has the solar industry's first pre-funded collection and recycling program for their product which is administered through a trust mechanism ensuring that funds are available to collect and recycle the end-of-life panels at no extra cost to the user. According to this, the cost of collection and recycling of the end-of-life panels are built into the product costing. Since collection and recycling is pre-funded, it is expected to act as an incentive to the user to opt for using the program. The collection and recycling funds are managed by a third party trustee so that even in case First Solar ceases to exist at a future date, the funds will be available for collection and recycling.

In the recycling process, the end-of-life (or broken, unusable) panels destined for recycling are crushed and the Cd/Te metals are extracted with strong acid in the presence of a strong oxidising agent. The extracted Cd/Te metals are then precipitated and the Cd/Te-rich precipitate is sent for metals recovery (Fig. 3). Water used in the entire operation is treated, first for organics removal and then through flocculation-sedimentation. The thickened wastewater clarifier underflows are filtered using filter presses and the wastewater filter cake containing very low concentrations of Cd are disposed of in a hazardous waste landfill. An EIA study done on the entire recycling process also reports the process to be acceptable [8].

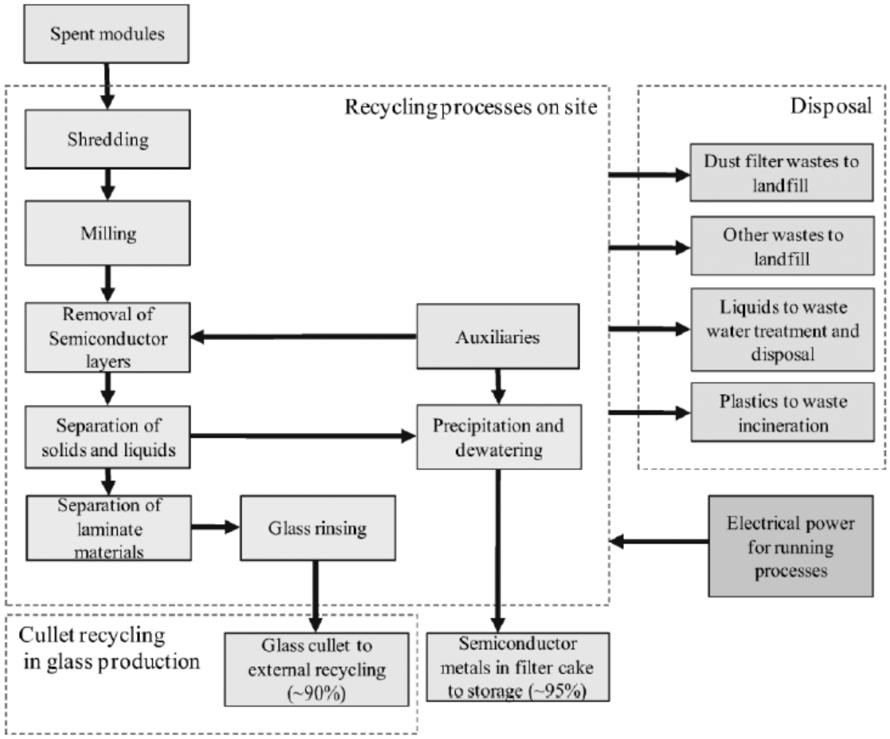

Figure 3. Flow chart of CdTe module recycling [8].

Summary

(i) Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product (including recycling)?

In summary, Cd and other heavy metals are an important issue in India and there exist several sources which contribute to the presence of such pollutants in water, soil and air. It may be important therefore to remark that given the care taken in production of CdTe PV modules and the little or no possibility of Cd being released from the modules deployed in the field, there should be little reason to be concerned that any addition can be done to the existing Cd (or other heavy metal) pollution levels. Module recycling also improves the long-term sustainability of CdTe PV technology and PV technology in general.

(ii) What are the overall life cycle impacts of the large-scale deployment of CdTe PV systems on the environment, public health, and public safety, taking into account other energy alternatives?

CdTe PV has the smallest carbon footprint and fastest energy payback period among PV technologies [19], and PV systems, particularly using the CdTe, have significant potential to mitigate global warming. Current power generation technologies using coal have a large amount of Cd emitted in the environment in an uncontrolled manner, with the amount far exceeding the expected emission from CdTe modules even under exceptional conditions (e.g., fire) [4]. Even the dominant PV technologies based on Si solar cells have larger life cycle Cd emissions due to the embodied energy being larger for these devices [5]. Life cycle analysis also suggests that a large growth in the CdTe PV sector has the potential to actually reduce, rather than increase, overall global cadmium-related environmental pollution [31].

1. Introduction

1.a Sustainable photovoltaic materials

Society faces grand challenges to sustain continued development in the 21st century. Photovoltaic (PV) installations can be inherently sustainable, as a fossil fuel-free significant power source, if we can continue to develop cheaper and efficient solar cells. A broad range of solar cell technologies is under active research and at different stages of module development and field deployment. In earlier days, the selection of materials for use in products has traditionally focused solely on the cost and the performance characteristics; now with the times, sustainability has become a significant factor too. Avoiding human health and ecological impacts requires their assessment at the level of materials selection in the early stage of product design and manufacturing. Environmental and human health impacts of material use can also damage society's ability to sustain the planet for the future generations.

To measure the sustainable activity of the PV technology, we need to look into the environmental, health and safety impacts and benefits along with the cost aspects, and the resource availability, and also in comparison with other, conventional energy generating technologies. The PV industry currently is largely based on silicon crystalline and multicrystalline Si wafers as first-generation solar cells, with somewhat high cost but very good performance in terms of efficiency. But silicon technologies can use potent greenhouse gases like NF_3 or SF_6 and require energy-intensive polysilicon production. Thin film PV technologies have opened the gates for achieving terawatts of power generation by meeting the cost goals required to achieve grid parity (which in some countries is indeed achieved!).

The thin film technologies require modest material demands, combining moderate efficiencies with low costs and low energy use. A key factor for the production of PV at the large scale is that costs will need to reach grid parity, which also includes the cell, module and the balance-of-systems costs. Many companies around the world are developing a variety of manufacturing approaches aimed at low-cost, high-yield, large area thin film and bulk device processes. Apart from the cost, the PV technologies should also concern the environmental impacts, which should be lower than the traditional power generation technologies and comparable to other renewable energy options.

Therefore, the manufacturers of established and under-development PV technologies are carefully considering sustainability in terms of the materials and energy involved in the technology. The newer device architecture are considering the possibility of PV reaching TW production levels which may give rise to a shortage in raw materials, since some of these are in short supply in the first place. This, and the aim to lower life cycle environmental impacts, has given rise to cradle to cradle technology development for different PV technologies by recycling the materials for used or non-performing modules so as to reconstruct the required materials. This also obviates the need to deposit the used modules into landfills, helping to manage large future waste volumes. End-of-life management of CdTe PV is described in Sections 2.b and 2.c below.

1.b Thin film Solar Cells

In the review paper "Thin Film Solar Cells (TFSC): An overview "by Chopra et. al., [9] it was stated that "Which cell(s) and which technologies will ultimately succeed commercially continue to be anybody's guess, but it would surely be determined by the simplicity of manufacturability and the cost per reliable watt. Cheap and moderately efficient TFSC are expected to receive a due commercial place under the sun."

The observation made about 8 yrs ago was prescient of things to come! The PV landscape completely changed with First Solar becoming the largest thin film solar cell producer (based on GW production) at production costs < $\$1/W_P$ with Q1 2012 average module efficiency $\eta \sim 12.4\%$. CdTe panels from First Solar with a compellingly low manufactured cost have recently emerged as one of the most successful second-generation PV approaches to date, and is currently at second place in the overall PV production level. First Solar is the largest thin film module manufacturer in the world with smallest carbon footprint and fastest energy payback period [19]. Other technologies (CIGS and a-Si:H) are also gearing up to reach these levels. The large-scale production can raise questions about material shortage – Earth Abundant Materials are the latest category of PV materials being actively researched, keeping the trend of the "Pyramid of PV materials" mentioned by M. Green [11]. Forecasted IEA thin film PV market shares through mid-century can be met by currently understood future raw material availability (of indium and tellurium), and further eased by innovation and technological developments (including efficiency increase, reduced absorber layer, and higher material utilization during the deposition process) [12].

1.c Cadmium Telluride Thin Film Solar Cells

As one of the technologically most viable PV materials, CdS/CdTe solar cells have attracted considerable attention. CdTe has a direct bandgap of 1.45 eV and high absorption coefficient of $\alpha \sim 10^5$ /cm in the visible region. About 1 μm CdTe thin film is enough to absorb 90 % of the absorbed light. Cd and Te elements have a significantly higher vapor pressure than the compound [1]. CdTe has strong ionicity (72%) and the chemical bond energy between Cd and Te is also > 5 eV [2]. The strong bonding leads to an extremely high chemical and thermal stability, reducing the risk of degradation of performance. CdTe solar cells have been treated with some concern regarding the material availability (Te is a rather scarce element) and toxicity of the elements. These concerns have been resolved to some extent by promotion of the counterview that CdTe-based photovoltaics can act to sequester Cd already being produced from Zn and Cu mining as a by-product [4] and by providing for recycling by the company at no additional cost to the user (see further discussion in Section 2).

1.d. Photovoltaics scenario in India

India has embarked on an ambitious programme on solarizing the country by exploiting the abundantly available solar energy throughout the country using both solar thermal and solar photovoltaic technologies for electricity as well as thermal energy. The Ministry of

New and Renewable Energy Sources (REF: www.mnre.gov.in) has launched the Jawaharlal Nehru National Solar Energy Mission (JNNSM) which has projected 22 GW of solar electricity generation by 2022. It is obvious PV technologies using different types of solar cells will have a major role in the mission. Both on-grid and off-grid systems will be deployed in urban, rural, and remote areas with centralized and distributed energy generation features. Typically, one expects that the PV systems will use any solar cell technology which can exploit the rich solar resource available in the country to convert it into electricity for operating diverse ac and dc loads. Though major Indian and international manufacturers are currently mainly using crystalline Si technology, the thin film solar cell companies are also making their presence felt. The advantages offered by thin film solar cell technology in using the diffuse light better and lesser thermal degradation can give a higher solar electrical energy output (in kWhr) compared to that obtained in Si solar cells. This happens even when the module efficiency is almost 20% lower in case of thin film solar cells (TFSC). The larger area required means larger costs in system erection can have a negative effect; however, one of those TFSC manufacturers, First Solar, is vertically integrated and controls BOS costs to stay competitive with higher efficiency module systems. The attractive pricing can be helpful in the promotion of TFSCs. As of now Si prices, particularly from the Chinese manufacturers, have brought the PV electricity prices quite low and one may see the combined effect of all the PV technologies in the price reaching grid parity within this decade.

Since it is expected that the users in India may range from individuals to large corporates or govt. agencies, the user profile in handling modules of different types can influence the module performance and life (which in turn affects the PV system performance and life). Therefore, any study involving materials like CdTe needs to keep a perspective of the users' understanding of the issues involved and their acceptance of different practices to be followed for different PV technologies. One example of what this could mean is that small-volume users may dispose of the modules on their own and may not take advantage of the recycling programme offered by the companies. In such a situation the effect of metals getting into the soil and then into the plant/water can be different from the cases where good practice of handling and disposing of the modules is followed (as prescribed by the module manufacturer). First Solar is focused on large scale (not small-volume) CdTe PV module deployment in on-grid (free field) installations; therefore the module recycling commitment can be a part of the installation and commissioning protocol between First Solar and its customers.

1.e. Cadmium related issues in India

The presence of Cd in the environment can vary from country to country. India is having serious concern about heavy metal in water bodies, food products, plants, and in air. An analysis below has been done to understand how the presence of Cd in the environment is coming about due to different industrial products and what the reported levels are in the country. This may be useful when comparing these levels to the extent CdTe PV systems could add to the Cd presence. Though a lot of heavy metal incorporation into the environment may be due to bad practices in disposing the industrial waste, the PV industry's attention to managing environmental pollution in all the aspects of fabrication and deployment can be a pointer to the right practices that need to be followed in the country. Some details on the source of cadmium in Indian environment are given below.

In India as in other countries, cadmium is recovered as a by-product in zinc smelting and refining. The concentration of cadmium in sphalerite, the principal ore of zinc, ranges from 0.03 to 9.0 wt%. In zinc concentrate at Rampura Agucha, Bhilwara district of Rajasthan state of India (world's largest deposits of zinc and lead), cadmium is 0.18% while in lead concentrate the cadmium is 150 ppm. There are no separate resources of cadmium. The total installed capacity for recovering cadmium in India was 913 tonnes of which Hindustan Zinc Ltd. accounted for 833 tonnes. Binani Zinc Ltd reported the remaining 80 tonnes capacity.

In India, cadmium is consumed in industries like paint, glass and chemical. There are many reports where Cd presence in food product and items of regular uses has been reported:

(i) In Coca-Cola waste

Kerala State Pollution Control Board analyzed the waste material emitted by the Coca-Cola plant and found that cadmium was present in much higher concentration than the permissible level. In fact, the concentrations of Cd, Cr and Pb in the water bodies were much above permissible limits.

(ii) In gold jewelry

Cd has been used to join the end in gold jewelry and the practice is officially banned due to the ill effects of Cd.

(iii) In Indian toys

Colorful building blocks or toys may contain lead and cadmium which can be harmful to children.

(iv) In food

Foodstuffs and drinking water in different parts of the country are found to contain high levels of heavy metals (arsenic, mercury, nickel, lead, cadmium, etc) which accumulate in body tissues and cause a variety of ailments. Green leafy vegetables contain high amount of lead, chromium, arsenic, mercury and nickel. Turmeric samples contained arsenic, cadmium and lead. Mainly the use of sewage water and industrial effluents for irrigation is responsible for accumulation of heavy metals in vegetables. Untreated industrial waste water can make a large percentage of groundwater unpotable due to the presence of Cd and other heavy metals.

(v) Adsorption of cadmium on river bed sediments

A detailed study of Cadmium adsorption based on experimental data in river bed has been reported [13]. The effect of operating variables, like solution pH, sediment dose, contact time and particle size on the adsorption of cadmium ions on bed sediments of the highly polluted Kali River in western Uttar Pradesh has been studied. The study has shown the potentiality of freshly deposited sediments in adsorbing cadmium ions, which may enter the river system through the disposal of municipal & industrial effluents or by biological & chemical degradation. The study indicates that though the cadmium ions have more affinity for the clay and silt fraction of the sediment, the overall contribution of coarser fraction to adsorption is more than the former.

The ingress of heavy metals in aquatic system in the country has been increasing over the years, since the industrial usage involving these metals have tremendously increased, with poor administration in discharge of the effluents [14]. Cd has been found in the aquatic systems through the wastewater from the electroplating industries, dyeing industry, fertilizers etc. Stringent standards for the permissible limit of Cd for the discharge of wastewater (0.1 mg/L) and drinking water (0.05 mg/L) have not been effective. The effects of the presence of heavy metals in water bodies have also affected the ground water in neighboring areas. Since a large population depends on groundwater for the potable water requirements, there can be serious health implications of using such water for daily consumption.

Cadmium, used in a large number of industrial applications like batteries, coating of stabilizers, paint, and alloys is toxic even at very low concentrations. One of the most promising plants for the extraction of heavy metals such as Cadmium from contaminated sites is Brassica juncea commonly known as Indian Mustard (Rai). Its roots help in removing zinc, lead, chromium, copper, selenium and nickel as well. Barley (Hordeum vulgare) and oat (Avena sativa) take in metals such as copper, cadmium and zinc. Spiny Amaranths (Amaranthus spinosus) and Alligator weed (Alternanthera philoxeroides; the semi aquatic weed one sees on most polluted rivers) grown on the sewage sludge of Musi river in Hyderabad have shown that they can concentrate cadmium, zinc and iron in their leaves. They can be used to restore sewage sludge contaminated sites [15].

The study - 'Airborne inhalable metals in residential areas of Delhi, India: distribution, source apportionment and health risks' - was carried out by the Jawaharlal Nehru University, Delhi researchers through air sample monitoring at three locations [16]. The locations for the study were chosen because of their proximity to coal-fired power plants and industrial areas. It was noted that “We cannot do much about metals that are naturally present in the air but metals such as zinc, nickel, chromium and cadmium are more because of anthropogenic factors". The table (taken from the published report) gives the details of the different amounts at the three locations (calls RG- Rajghat; MV-Mayur Vihar ; and MP-Mitha Pur) in different seasons.

The most abundant metals were Fe and Zn with concentrations in the range of several µg m^{-3}, whereas Cd was the least abundant with concentration ranges of several ng m^{-3}. It is evident that the concentrations of inhalable metals in residential areas of Delhi – although

Table 1 - Seasonal and spatial distribution of ambient PM10 and associated metals (µg m^{-3}).Also shown are the results of two-ways ANOVA test (F-values along with corresponding significances levels).

Table 1. *Seasonal and spatial distribution of ambient PM_{10} and associated metals (µg m^{-3}). Also shown are the results of two–way ANOVA test (F–values along with corresponding significance levels)*

	RG			MV			MP			RG (N = 43)	MV (N = 44)	MP (N = 44)	*F*–values two–way ANOVA		
Species	W	S	M	W	S	M	W	S	M	Mean ± SD	Mean ± SD	Mean ± SD	Season	Site	Season*Site
PM_{10}	165.1	205.8	133.8	184.7	210.3	122	194.9	215.9	164.2	166.5 ± 54.7	175.5 ± 67.6	192.3 ± 63.4	17.2^{c}	2.2^{NS}	0.6^{NS}
Fe	7	12.1	5.5	9	12.4	6.7	10.5	13	10	8 ± 3.7	9.6 ± 4.4	11.2 ± 4.3	23.2^{c}	7.7^{b}	1.2^{NS}
Mn	0.34	0.37	0.26	0.27	0.37	0.21	0.22	0.32	0.2	0.32 ± 0.1	0.29 ± 0.1	0.25 ± 0.1	14.2^{c}	4.5^{a}	0.7^{NS}
Cd	0.014	0.005	0.005	0.022	0.014	0.011	0.028	0.018	0.011	0.008 ± 0.006	0.016 ± 0.01	0.019 ± 0.015	19.2^{c}	16.1^{c}	0.7^{NS}
Cu	0.28	0.16	0.08	0.25	0.34	0.22	0.26	0.21	0.16	0.18 ± 0.1	0.27 ± 0.1	0.21 ± 0.1	12.3^{c}	8.6^{c}	4.5^{b}
Ni	0.44	0.32	0.15	0.39	0.3	0.13	0.46	0.39	0.25	0.3 ± 0.2	0.28 ± 0.2	0.37 ± 0.2	49^{c}	7^{c}	0.5^{NS}
Pb	0.41	0.24	0.14	0.47	0.49	0.25	0.51	0.54	0.33	0.27 ± 0.2	0.41 ± 0.2	0.46 ± 0.3	17.8^{c}	13.3^{c}	1.5^{NS}
Zn	4.4	4.4	5.3	5.3	4.7	2.7	5.7	4	2.6	4.7 ± 1.7	4.3 ± 1.5	4.1 ± 2.1	11.7^{c}	1.8^{NS}	8^{c}
Cr	0.17	0.17	0.07	0.32	0.17	0.09	0.32	0.27	0.09	0.13 ± 0.07	0.2 ± 0.12	0.23 ± 0.18	36.3^{c}	8.7^{c}	3.2^{b}

W, S and M denote winter (November – February), summer (March – June) and monsoon (July – October) seasons, respectively; Mean ± SD refers to the annual mean values ± one standard deviation at the sites; N denotes the number of samples collected at a particular site; Level of significance: ^{NS}not significant, $^{a}p<0.05$, $^{b}p<0.01$, $^{c}p<0.001$.

comparable, in some cases, with other Indian and Asian cities – are often more than an order of magnitude greater than their European or US counter–parts. Overall, it was observed that concentrations of PM10 and a number of metals at the chosen residential areas of Delhi were distinctly higher than those at the urban background site. Concentrations of Cd, Ni and Pb at MP were significantly higher ($p<0.05$) than RG. Proximity to a major coal–fired power plant and an industrial area could be the reasons for higher metal concentrations at MP.

Enrichment Factors (*EF*s) of metals were calculated as EF = $(X_{aerosol}/Ref_{aerosol})/(X_{UCC}/Ref_{UCC})$ where X is the element under consideration both in aerosol and the upper continental crust (UCC), and *Ref* is a reference element that is typically crustal such as Al, Fe, Li, Ti etc. The third group represented by Zn (244.9 ± 155 – 418.3 ± 243) and Cd (386.1 ± 409.8 – 595.3 ± 397.5) had extremely high *EF* values (between 100 – 1,000) and were anomalously enriched in aerosol. Vehicular tire wear, battery–manufacture, pigments, metal plating and smelting industries are important sources of these metals. Metals such as Cd, Ni, Zn and Cr, on the other hand, had significantly higher concentrations in winter (multiple comparisons, $p<0.05$) and were negatively correlated with temperature, wind speed and the number of bright sunshine hours. These metals have important anthropogenic sources such as metal smelting (Zn), battery manufacture (Cd, Ni), oil combustion (Ni) and vehicular emissions (tailpipe/abrasion) (Zn, Cd, Cr). Emissions from these sources are trapped and stabilized under inversion layers in winter, leading to higher abundances in ambient aerosol.

Three factors were identified that explained 75.5% data variance at MV. PC1 was loaded with Cd, Ni, Pb, Zn and Cr, possibly indicating industrial emission sources from the Patparganj Industrial Estate. PC2 was highly loaded with Mn, Cd and Cu, and to a lesser extent with Fe, denoting vehicular resuspension of road dust and brake–drum abrasion particles. PC3 was loaded with Fe and Pb indicating resuspension of crustal and road–dust possibly containing residual Pb–additives.

The overall annual averages of Ni and Cd in this study (316 ± 161 and 14 ± 12 ng m^{-3}, respectively) were around 15 and 3 times higher than the stipulated standards (NAAQS for Ni: 20 ng m^{-3} and the European Union target for Cd: 5 ng m^{-3}, EU Directive 2004/107/CE). As per US EPA's weight–of–evidence, Ni is classified as a Group A pollutant (known human carcinogen) while Cd is classified as a Group B1 pollutant (probable human carcinogen). Societal Incremental lifetime cancer risk (ILCR) was calculated assuming Delhi's population to be 17 million and it was found that up to 2,908 excess cancer cases (102 for Cd, 2 559 for Cr (VI) and 247 for Ni) are possible in Delhi considering lifetime inhalation exposure to these pollutants at their current concentrations.

It is clear that the presence of Cd and other heavy metals has several different origins in the country and increasingly the ill effects due to these on the air, water and plants in different parts of the countries are being observed. There is a need for better management of the sources of these metals and the methods of removal or trapping by different methods (plants e.g.) need to be become more prevalent in order to prevent spread of these metals any further.

In sum, the above analysis has been done to understand how the presence of Cd is coming about due to different industrial products and what the reported levels are in the country. In contrast, the PV industry's concern about the environmental pollution can lead to the development of right practices that need to be followed and further promoted in the country.

1.f. Project Objectives

The project undertaken by us has two main questions to be probed:

(i) Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product (including recycling)?

(ii) What are the overall life cycle impacts of the large-scale deployment of CdTe PV systems on the environment, public health, and public safety, taking into account other energy alternatives?

1.g. Malaysia visit report:

The team consisting of Prof. V. Dutta, Prof. T. R. Sreekrishnan, Dr. V. K. Komarala, and Prof. U. P. Singh visited First Solar's CdTe PV module production and recycling facility Kulim (plant 5 and 6) at Kulim Hi-Tech Park, Kedah Darul Aman, Malaysia on 21st and 22nd May, 2012. The project team visit was for understanding and evaluation of the environmental, health and safety (EHS) issues and benefits related to CdTe module production and recycling, and also the EHS practices being followed by the company.

During the first day (21st May, 2012), Director, Sustainable Development & Environment, and also Director of Product Safety for First Solar gave presentations, and we also had a guided tour in the production plant.

In the introductory presentation, a brief history of the company was given; it was formed in the year 1999 and started producing CdTe thin film photovoltaic modules from the year 2002. First Solar, Malaysia plant presently produces 2/3 of their CdTe modules in six production facilities, while the Ohio, USA and Frankfurt-Oder, Germany plants produce rest 1/3. The CdTe PV module and manufacturing process is a fully integrated, automated, and continuous thin film process. In the presentation they have showed the historical improvement of the average conversion efficiency from the 7.1 % in 2002 to 12.4% at present, along with long term stability data related to outdoor field testing. The steps involved in the CdTe module production process, the time required for making the module, and the implementation of the bar-coding before thin film coating on the glass substrate for future identification to take back and recycling were explained. Before the site visit, the ventilation and air filtering process using high efficiency filters were discussed.

The production process starts from cleaning of the TCO coated glass substrates (60 cm x 120 cm), thin (sub-micron scale) CdS deposition using PVD process and the thicker (micron scale) CdTe absorber layers in multiple chambers using the First Solar proprietary process. The contact deposition is done by sputtering. In between, the cell isolation for integrated module fabrication is done using laser scribing. In fact, a new laser system was under installation and the possibility of Cd containing debris being released was taken care by providing proper coverage to the entire process equipment. Prof. Singh pointed out that the edge isolation by sand blasting was the process used for module fabrication which could also release Cd. It seems that recently First Solar has discarded the sand blasting and adopted a laser based process. The Cd containing layers are carefully collected in a chamber and then recycled. The module testing under light and other standard conditions ensure that the modules are capable of performing as per the required specifications in the field conditions.

The second day was focused on the module recycling, safety overview, and Occupational Health (OH) and Industrial Health (IH) issues. The First Solar vision is zero occupational illness with the proper mechanism to identify, evaluate and control the sources of occupational health risk. The responsible IH team structure was shown for the KLM plant, which is headed by the Asia EHS director and managed by KLM IH manager. The complete IH team consists of safety and health, chemical safety, exposure assessment, hearing conservation, radiation safety and indoor air quality. The First Solar Industrial hygiene programme includes the cadmium management, IH exposure assessment, respiratory safety, ventilation and HEPA testing, laser safety, inert gas safety, and lead safety. The very important industrial hygiene management is related to cadmium and during the presentation, it was mentioned the KLM has comprehensive set of written programs and policies for the cadmium control with the state-of-art HEPA filtration systems, personal protective equipment, periodic blood and urine analysis. The permissible exposure limit (PEL) is the level set by regulatory agencies to which an employee may be exposed for a given time without respiratory protection. In the Malaysia the 8 hr PEL is 10$\mu g/m^3$, while First Solar has an internal limit of 1$\mu g/m^3$ globally. The USA PEL for cadmium is 5 ug/m3.

First Solar also employs Industrial hygiene air sampling strategies for ensuring a safe workplace, the manufacturing areas of a facility are air sampled frequently to identify and mitigate any risk. The cadmium air sampling was done by personal as well as area samples. The associates carry sampling equipment while performing a task; this method of sampling will measure potential exposure during sampling period. In the area sampling process, the samples will be collected from the specific location, which will measure the cadmium level at the area. The air sample tests were shown during the normal operation below permissible exposure limit; the average cadmium level in the manufacturing area is 0.17 $\mu g/m^3$, while the recycling area is around 0.19 $\mu g/m^3$.

Under the occupational health, we also had presentation on biological monitoring; once the person is exposed for more than 30 days per year, his blood and urine samples will be monitored by the First Solar. Their safety programs have kept levels of cadmium exposure low, within the reference values, like cadmium present at 0.94 in blood against 5.0 action levels and urine is 1.6 against 3.0 action levels. We also understood that every person has some accumulation of cadmium in their body; slowly our body will also eliminate some cadmium. The major source for cadmium in our body is due to our diet; foods high in cadmium includes organ meats, leafy vegetables, potatoes, grains, peanuts, soybeans and food grown in cadmium polluted water or soil. First Solar's earlier data confirms that the results overall are well below regulatory limits, validating control of cadmium exposure at First Solar.

As observed in the site visit, the internal studies as well as studies by outside agencies have established that the practices followed by the company are of highest standard, taking into account the chemical properties of the materials involved in production. The same established safety procedures are being followed in all the First Solar production plants. First Solar has established an OH & Safety management system which eliminates and minimizes any risks to the employees and the visitors. One element of that system/approach is that we were also required to change the footwear and use goggles and earplugs during the plant visit. The life cycle analysis data presented also showed that the CdTe technology emits insignificant amounts of Cd and other toxic materials while providing all the benefits known to be associated with PV [17].

The visit to the recycling plant also brought out the steps being done to process the modules to recover the usable materials. The Malaysian facility will have the largest recycling and processing plant within First Solar and will be able to reduce the requirement for transporting the modules from the installations from the nearby countries to German facility as is being currently done. In fact, there can be an issue involving government permissions in exporting and importing modules. This will require the company to continue working with the Malaysian government on a solution.

2 Results and Discussion

2.a Environmental impacts from CdTe Photovoltaics

There are no direct adverse effects from the PV industry on environment and health [12, 18]. Life-cycle-analysis conducted by Fthenakis in 2004 [4] at Brookhaven National Laboratory, USA, gives a comprehensive description of emissions associated with the production of the raw materials related to Cd and Te. The study focuses on analyzing the inventory of materials and energy flows in and out of a product, and assessing the impact of such flows. For example, (1) Production of Cd and Te, (2) Manufacturing of CdTe PV, (3) End of Life Disposal/Recycling and (4) total atmospheric emission, a comparison with other energy technologies is also presented. Fthenakis et al. [5] reported after life-cycle-emissions analysis, that photovoltaic systems have emissions of about 17 to 39 g of CO_2e/kWh, when compared to the 500 to 1100 g of CO_2 e /kWh from the fossil-fuel plants, with CdTe PV having the smallest carbon footprint and fastest energy payback period among PV technologies. Apart from the greenhouse gases in the life-cycle analysis, it was found out that other pollutants like SO_2, NO_x and particulate matter from the photovoltaic industry is about ~2-4% of those from conventional fossil-fuel plants [5]. Fthenakis et al., [5] has also evaluated life-cycle emissions from using fossil-fuel-based energy to produce the materials for solar cells (smelting and production), modules, and systems. According to the paper the greenhouse gas (GHG) emissions from Si modules are 30 – 45 g CO_2 eq/kWh, and the energy payback time (EPT) of such modules is 1.7–2.7 years. The corresponding figures for CdTe PV modules (frameless) are 24 g CO_2 eq/kWh and 1.1 years for ground-mounted installations. CdTe PV modules have about half the GHG emissions of crystalline Si. It can be concluded that PV systems, particularly using the CdTe have significant potential to mitigate global warming. Since the lifetime of PV systems are supposed to exceed 20 years, a low EPT means that a system can recover the energy required to pay for itself more quickly and displace grid electricity for the remainder of its lifetime. A summary is given in Table 2.1.

Table 2.1: GHG emissions and EPT [5].

PV type	Assumption	GHG emissions	EPT
Si modules	Rooftop-mounted, 0.75 PR, 1,700 $kWh/m^2/yr$	30 – 45 g CO_2eq/kWh	1.7 – 2.7 years
CdTe	Ground-mounted 0.8 PR, 1,800 $kWh/m^2/yr$ 30-year lifetime	24 g CO_2eq/kWh	1.1 years

Now we need to look into the details of heavy-metal (Cadmium) emission from the CdTe PV industry into the environment, during production and operation of the solar cells and systems. During manufacturing of CdTe solar cells, the amount of emission will be around 0.016 grams per gigawatt-hour of energy [4] when compared to 2 grams of cadmium emission per gigawatt-hour generation from the coal based power plants [6]. It was also shown that ~ 89-98% reduction in the emissions of green-house gases, and reduction of other heavy metals like cadmium into the environment from the CdTe PV technologies compared to the fossil-fuel based power sources [5]. As part of strategies for reducing the environmental releases of cadmium [4], the first step should be to cut back on producing and consuming zinc, which is difficult as zinc is used for galvanizing steel, and the second is to use cadmium in ways that prevent its flow to the environment. For example as discussed further in section 2.4, life cycle analysis suggests that a large growth in the CdTe PV sector has the potential to actually reduce, rather than increase, overall global cadmium-related environmental pollution. The flow of the cadmium into the environment from the CdTe PV industry also depends on the method of preparation of CdTe thin films and associated engineering controls for air emissions and wastewater treatment.

Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption are also evaluated for ribbon-Si, mc-Si, mono-Si, CdTe, hard coal, lignite, natural gas, oil, nuclear, hydro, and UCTE (Union for the Coordination of the Transmission of Electricity) average. Compared to the Cd emissions from oil at 43.3 g/GWh, the PV system emissions are much lower and in particular for CdTe modules 0.3 g/GWh (Table 2, also given earlier in Fig.1).

Table 2.2: Atmospheric Cd emission [5]

PV type and fuel type	Atmospheric Cd emissions
Ribbon-Si	0.8 g/GWh
mc-Si	0.9 g/GWh
Mono-Si	0.9 g/GWh
CdTe	0.3 g/GWh
Hard coal	3.1 g/GWh
Lignite	6.2 g/GWh
Natural gas	0.2 g/GWh
Oil	43.3 g/GWh
Nuclear	0.5 g/GWh
Hydro	0.03 g/GWh
UCTE average	4.1 g/GWh

The impact of geography on the energy payback time and carbon footprint of commercial PV modules was investigated by Mariska de Wild-Scholten [19]. For commercial roof-top flat plate PV systems, the energy payback time and carbon footprint vary considerably for silicon based modules based on the actual country mix. The energy payback time and carbon footprint of CdTe thin film PV technology is less sensitive to country energy mix due to the lower electricity consumption of CdTe PV module production compared to the Silicon based PV technologies. In this case study, the systems were assumed to be installed in Southern Europe (1700 kWh/m^2.year) and the

- Energy payback time ~0.8 (CdTe) -1.7(Si) years,
- Carbon footprint ~19 (CdTe)-34 g (Si) CO_2-eq/kWh.

Mariska de Wild-Scholten et al., [20, 21] also explored the life-cycle impacts, and pointed out the factors which can be considered for reducing the life cycle impacts. For the three PV technologies (Silicon, CdTe and CIGS), they concluded that the environmental impact of all the technologies is highly affected by the electrical energy used in the production. To reduce the environmental impacts of any PV technology and improve sustainability, , one should consider (a) Reduce energy consumption or use renewable energy for producing PV modules, (b) Reduce material consumption (less glass, no framing), (3) Reduce emissions (SF6/NF3, toxic materials), (4) Increase module efficiency, (5) Increase lifetime and (6) Recycle materials

It is clear that the production of the power from the CdTe thin-film photovoltaic technologies have benefits compared to fossil-fuel based technologies; now the issues are related to: (1) modules routine operation, (2) emissions and encapsulation of cadmium in CdTe PV modules during catastrophic events (e.g., fires) after deploying solar photovoltaic modules large scale in the fields, (3) situations like rainwater leaching of cadmium from broken modules, and (4) what will happen after their useful life.

There is no concern of Cd emission from these panels during their routine installation and operation phases. It was demonstrated in the environmental risk assessment that during the unexpected fires after installation, nearly 99.96% of cadmium will encapsulate safely in the glass [4, 6]. The leaching of cadmium from the CdTe modules is minimal and does not pose environmental or health risks; CdS and CdTe semiconducting layers are sandwiched between two layers of glass at high temperature with an industrial laminate [12], and the solubility product of CdTe is extremely low ($K_{sp} = 9.5\times10^{-35}$) [3], the melting point of CdTe is 1041 ^{0}C, and evaporation begins at 1050 ^{0}C, which can happen only with huge fires. Because of the large percentage of encapsulation, there is minimal ambient air dispersion and migration to ground water in case of rain during the fire. The in-field module breakage rate is only 0.04% per year [22]; there may be some breakages during shipping and installation, but First Solar has a pre-funded take back and recycling process. After installation, routine inspections and power output monitoring diagnose broken modules that need to be taken back to designated sites for recycling. First Solar also provides module recycling at the end of their useful lifetimes for all users through an independent funding and management.

2.b Materials recycling: Environmental & economic benefits

As an example of the importance of end-of-life management, one-third of the world's copper is currently found in landfills, rather than being incorporated in useful applications [23]. Recycling will save raw materials to a large extent, chemical byproducts will be reduced, and conservation of energy/electricity will be achieved. Future world needs will require materials that are fully recyclable and the manufacturers to adopt the cradle to cradle approach that can support the remanufacturing of components from spent products into new products or the same products. A very good strategy to mitigate resource availability risk is recycling. Recycling can reduce primary-resource depletion and generally should reduce the environmental impacts; it can reduce the material costs and diversify the supply chain, reducing the impact of limited availability. Shortage can be particularly important as the industry attempts to scale PV power generation from present levels to the terawatt levels needed to meet a significant fraction of the world's electricity needs.

At the same time materials are geologically distributed unevenly, and the extraction requires various amounts of efforts. Significant material challenges exist for thin film PV devices based on cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIGS), but the availability of tellurium for CdTe cells, and gallium, indium for the CIGS cells is a matter of concern for terawatts production, since these are relatively rare in the earth crust. Tellurium is one of the four rare (Ge, Ga, In and Te) materials at risk for future demand, by keeping in mind the potential high growth of the future PV industry. As cadmium and tellurium are both by- products of zinc, copper and lead production, the energy to extract the elements may pose an additional limitation for the PV industry. However, forecasted IEA thin film PV market shares through mid-century are expected to be met by currently understood future indium and tellurium availability [24]. In addition, material availability concerns will be eased with future enhanced recovery during primary production, reductions of the thickness of semiconductor layers, increases in the efficiency and life expectancy of modules, and recycling of end-of-life modules [12].

As the PV technology continues to make large strides all over the world (especially in the countries where policy makes PV generation a preferred option), the issue of end of life PV system decommissioning has attracted attention. All the PV technologies are expected to be either cradle to grave or cradle to cradle in order not to become a potential source of pollution after the modules reach end of life. In fact, the paper by Held and Ilg [25] clearly brings out the possibilities available for end of life treatment including recycling the material recovered in the process. It is indeed possible that the recovery of the materials used (Cd and Te in CdTe module, e.g.) in module fabrication can be reconstituted to make the same cell architecture, which in turn can lessen the possibility of these materials running out even if the PV electricity goes to terawatt level and beyond. The cost implication may have a dampening effect, but given the fact that other electricity generation alternatives based on conventional sources have to be scaled down or retrofitted with controls for climate change reasons, the cost factor may not limit the recycling option. If there are any ways by which the toxic components gets into the water or food chain, the process need to be improved to avoid such possibilities. Currently, air emissions controls and on-site wastewater treatment processes keep Cd and other emissions from recycling below permissible regulatory limits.

When we are looking at the module manufacturing, and the recycling, the greatest challenge might be to ensure high recovery rate from the used modules. First Solar is working on this through the development of a recycling infrastructure. The process of recycling is a great challenge due to the heterogeneity of materials in most of the products; the investment in technology is very much essential along with the customer participation and it will be a challenging economics. For example, separating the polymeric materials and semiconducting materials from the glass is an engineering challenge. However, First Solar is currently operating CdTe PV recycling processes at a commercial scale and currently incorporates collection and recycling costs into its module price. In the recycling process, toxic emissions are much lower in the life cycle of thin-film PV (particularly CdTe) than in the life cycles of alternative PV and conventional power systems [18]. First Solar has a "cradle to cradle' approach for the panels they manufacture. This approach can mitigate toxicity, resource efficiency and scarcity concerns. Efforts to reduce the thickness of the active layer for a given efficiency also reduce the amount of material needed, easing the material availability issue to some extent [12].

2.c First Solar efforts for recycling CdTe PV modules

To demonstrate environmental responsibility, First Solar has implemented a module collection and recycling programme as part of its overall environmental sustainability approach, which is an integral part of the product offering, and will minimize municipal landfill use. It is designed for creating sustainable energy supply by combining affordable solar modules with a product life cycle management approach, with free of cost collection and recycling. All modules are also labeled with recycling contact information. The recycling technology is designed to recover valuable raw materials, maximize the amount of material recycled, and minimize the environmental impacts. Estimated recovery of Te and Cd is up to ~95% in the recycling process; the unrefined semiconductor material further processed by a third party recycling partner to create semiconducting material for use in new modules. Up to ~90% of the module weight is recovered; most of this is glass, and it will be used in new glass products. Apart from that, recycling could reduce the overall life cycle impacts by 6% to 10% and ~2% in the primary energy demand [26]. In the recycling process during our plant visit, we have seen the effective dust control process, which are equipped with pre-filters and high efficiency particulate air filters, which are 99.95% efficient [27].

2.d First Solar Reports & Literature

In fact the papers and the reports provided by First Solar have been critically examined and the major conclusions (as also discussed above) are: (1) indeed the amount of Cd compounds that is contained in CdTe PV systems is extremely small ($<0.1g/W_P$) and given the First Solar program of module recycling the chance of Cd compounds and other potentially harmful materials getting into the ambient environment from the PV plant during its life time is also negligible, and (2) current power generation technologies using coal have a large amount of Cd emitted in the environment in an uncontrolled manner, with the amount far exceeding the expected emission from CdTe modules even under exceptional conditions (e.g., fire). Even the dominant PV technologies based on Si solar cells have larger life cycle Cd emissions due to the embodied energy being larger for these devices [5].

In detail study for example, Golder Associates (UK) (2010) [28] reviewed and commented on the reports submitted by NGI on “Environmental Risks Regarding the use and final disposal of CdTe PV modules and leaching from CdTe PV modules”.

NGI on their part have undertaken a detailed study and have examined European Union waste classification, leach testing as well as search for life cycle assessment and toxicity of Cd and Te. They concluded that, CdTe is a non-hazardous waste and the leaching potential of the module is small. The results of leach testing indicate that end-of-life PV modules would meet the requirements for disposal of stable non-reactive hazardous wastes disposed of in a non hazardous waste site. In addition, as First Solar operates a pre-funded take back programme for end of life modules thereby minimizing the risk of disposal in a landfill or in an uncontrolled manner.

Turney and Fthenakis [29] discuss the environmental issues related to the installation and operation phases of large scale power plants in detail. To identify the environmental impacts due to installation and operation of large-scale solar power the author have reviewed the published literature extensively and divided their studies in following sub sections;

- – Land use,
- – Human health and well-being,
- – Wild life and habitat,
- – Geo- hydrological resources,
- – Climate and greenhouse gases.

The conclusion was that the solar power plants located in true deserts (< 3 cm annual rainfall) and other locations where solar insolation is intense and where there is very little wildlife or biomass, have the most beneficial environmental impact. Overall, large-scale, ground-mounted solar PV power plants are largely beneficial with regards to environmental indicators relative to traditional fossil-fuel based power generation.

The impacts of above points are reproduced below:

Table 2.3(i) - Impacts to wildlife and habitat of solar energy relative to traditional U.S power generation

Impacts to wildlife and habitat of solar energy relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Acid rain: SO NOx	Reduces emissions	Beneficial	Moderate	Solar power emits ~25× less
Nitrogen, eutrophication	Reduces emissions	Beneficial	Moderate	Solar emits much less
Mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Other: e.g., Cd, Pb, particulates	Reduces emissions	Beneficial	Moderate	Solar emits much less
Oil spills	Reduces risk	Beneficial	High	Note: BP Horizon Spill, Valdez Spill
Physical dangers				
Cooling water intake hazards	Eliminates hazard	Beneficial	Moderate	Thermoelectric cooling is relegated
Birds: flight hazards	Transmission lines	Detrimental	Low	Solar needs additional transmission line
Roadway and railway hazard	Reduces hazard	Beneficial	Low	Road and railway kill is likely reduced
Habitat				
Habitat fragmentation	Neutral	Neutral	Moderate	Needs research and observation
Local habitat quality	Reduces mining	Beneficial	Moderate	Mining vs. solar farms; needs research
Land transformation	Neutral	Neutral	Moderate	Needs research and observation
Climate change[a]	Reduce change	Beneficial	High	Solar emits ~25× less greenhouse gases

2.3(ii) - Impacts to climate change from solar power, relative to traditional U.S Power generation

Impacts to land use and geohydrological resources relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Soil erosion				
During construction	Less soil loss	Beneficial	Low	Existing mitigation is sufficient
During routine operation	Unknown	Unknown	Moderate	Needs research and observation
Surface water runoff				
Water quality	Improves water quality	Beneficial	Moderate	Needs research and observation
Hydrograph timing	Unknown	Unknown	Low	Needs research and observation
Waste management				
Fossil fuels waste spills	Eliminates waste stream	Beneficial	Moderate	Solar avoids fly ash spills and oil spills
Nuclear waste stream	Eliminates waste stream	Beneficial	High	Solar avoids need for waste repositories
Groundwater				
Groundwater recharge	Unknown	Unknown	Moderate	Needs research and observation
Water purity	Improves water quality	Beneficial	Moderate	Needs research and observation

2.3(iii) – Impacts to land use and geohydrological resources relative to traditional U.S power generation.

Impacts to climate change from solar power, relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Global climate				
CO_2 emissions	Reduces CO_2 emissions	Beneficial	High	Strong benefit
Other GHG emissions	Reduces GHG emissions	Beneficial	High	Strong benefit
Change in surface albedo	Lower albedo	Neutral	Low	The magnitude of the effect is low
Local climate				
Change in surface albedo	Lower albedo	Unknown	Moderate	Needs research and observation
Other surface energy flows	Unknown	Unknown	Low	Needs research and observation

A report by Bavarian Environmental Protection Agency (2011) on "*Calculation of emissions in case of fire in a photovoltaic system made of Cadmium Telluride modules*" mainly considers the effects of CdTe modules on the neighborhood and the general public in the case of fire [30]. The expected emission concentrations were calculated depending on the distance to the fire site, and the results were compared with the evaluated results for the corresponding air pollutants.

The distribution calculation was performed using the computer program STOER V2.23 (R. Röckle, TÜV Umwelt GmbH, Freiburg, 1994) with several assumptions. The distribution calculations were performed for the given cadmium contents in the modules: **Case 1:** 14.0 g Cd/m^2 (average cadmium contents in CdTe modules) and **Case 2:** 66.4 g Cd/m^2 (maximum value). Fire areas of three different sizes were considered each time (50 m^2, 500 m^2 and 1,000 m^2) and the Heat input was taken as 6MW, 10MW, 60MW, 100MW and 200MW.The value of Cd emissions were compared with AEGL-2 values (Acute Exposure Guideline Levels). It was finally concluded that (using distribution calculation) a serious danger for the immediate neighborhood and general public can certainly be excluded when modules containing CdTe burns.

In another article Fthenakis et al., [6] have reported on emission and encapsulation of Cadmium in CdTe PV modules during fire. The study is based on glass to glass laminated CdTe PV modules. Pieces of commercial CdTe photovoltaic modules, sizes 25 cm x 3 cm, were heated to temperatures up to 1100^oC to simulate exposure to residential and commercial building fires. The heating rate and duration in these experiments were defined according to standard Underwriters Laboratories (UL) and American Society for Testing and Materials (ASTM) test protocols.

Four different types of analysis were performed to investigate emissions and redistribution of elements in the matrix of heated CdTe PV modules:

(1) Measurements of sample weight loss as a function of temperature;

(2) Analyses of Cd and Te in the gaseous emissions;

(3) Cd distribution in heated glass using synchrotron X-ray fluorescence microprobe analysis;

(4) Chemical analysis for Cd and Te in the acid-digested glass.

For measurements of sample weight loss as a function of temperature, thermo-gravimetric tests were carried out. The pieces of PV module were placed on alumina plates and were positioned inside a quartz tube in the central uniform-temperature zone of the oven and heated for four different temperature viz. 760, 900, 1000 and 1100 ^{o}C. The quartz tube and glass-wool (used as filter) were leached for 24 h in nitric acid. Complete removal of the metals from the glass-wool filters was verified by additional leaching using hydrochloric acid and hydrogen peroxide solutions for 48 h in a tumbling machine. The acidic solutions from rinsing of the reactor walls, rinsing of the glass-wool filters in the reactor exhaust, and the scrubber liquids, were analyzed for Cd and Te by inductively coupled plasma (ICP) optical emission spectroscopy.

The weight loss and emission of Cd and Te as measured is tabulated and is reproduced here.

Table 2.4: Measured loss of mass

			Cd emissions		Te emissions	
Test	*T* (°C)	Weight loss (% sample)	(g/m^2)	(% of Cd content)	(g/m^2)	(% of Te content)
1	760	1·9	0·056	0·6	0·046	0·4
2	900	2·1	0·033	0·4	0·141	1·2
3	1000	1·9	0·048	0·5	1·334	11·6
4	1100	2·2	0·037	0·4	2·680	22·5

The synchrotron-based X-ray fluorescence microprobe analyses clearly show that Cd diffuses into the glass (earlier shown in Fig. 2). Comparison of the Cd line scans in the center and the edges of each sample, together with microscopic analysis of the perimeter of the sample, show that the small Cd loss occurs from the edges of the PV module through the space of the two glass sheets before they fuse together. This loss is likely proportional to the ratio of the mass of cadmium (i.e., area of the sample) to its perimeter, and as such would be smaller in full modules.

In the last experiment, pieces of heated samples were ground and fused with lithium tetraborate powder. The fused liquid was dissolved in HNO_3 and ICP analysis was performed for Cd and Te. The results of this analysis confirm that the Cd content remains constant, thus it is essentially retained into the glass matrix. The Te concentration in the burnt glass, at 1100 ^{o}C, was lower than the unheated sample, confirming the results of the air emissions analysis showing Te loss at the high temperatures.

Raugei and Fthenakis [31] deliberates on Cd flows and emissions from CdTe PV in Europe, taking into consideration three possible scenarios, with respect to current Cd emissions rates in Europe. The three possible scenarios are:

1. '***Pessimistic' scenario:*** this scenario assumes that support for the current incentives to the PV sector will not continue long enough for the technology to become competitive with bulk electricity.
2. ***'Reference' scenario:*** CdTe PV is presumed to keep growing at a faster relative pace, reaching 45% of the total PV market by 2025, concurrent with large gains in efficiency and reduced material demand. By 2050, newer, 'third-generation' PV devices are assumed to have overtaken CdTe PV as a widespread alternative.
3. ***'Optimistic' scenario:*** The relative role of CdTe PV within the PV sector is assumed to be the same as in the reference scenario, except that in this scenario, we set an upper boundary of 1 TWp for the cumulative installed capacity of CdTe PV by 2050, to account for possible constraints in the supply of tellurium.

Table 2.5: Cd demand scenarios for CdTe PV in 2025 and 2050.

Year and scenario	CdTe PV module efficiency(%)	Cd Te PV module lifetime (years)	Cd demand for PV modules (g/kWp)[a]	Cumulative installed capacity (GWp)	Yearly primary Cd demand for CdTe PV (tonnes)	Percentage of yearly global primary Cd demand[b] (%)
2008 'Base year'	10.5	30	165	1.2	100	0.6
2025 'Pessimistic'	12.5	30	97	25	149	1.0
2025 'Reference'	13.5	30	90	195	1790	11
2025 'Optimistic'	14.5	30	84	260	2700	16
2050 'Pessimistic'	12.5	30	69	240	324	2.2
2050 'Reference'	14	30	62	820	1310	8.5
2050 'Optimistic'	16	35	54	1000	2440	15

To track Cd emission flows, the life cycle of CdTe PV can be subdivided into four stages:

(i) Cd extraction and refining,
(ii) CdTe-powder production and PV-module manufacturing,
(iii) PV- module use, and
(iv) PV-module decommissioning.

The life cycle of balance of system (BOS) components are also included in the analysis. The average yearly Cd emissions associated with CdTe PV in the three future scenarios by supposing that the modules' characteristics remain at their initial values up to the end of the time spans considered (i.e., 2008–2025 and 2026– 2050). All emissions are calculated on the basis of the full life cycle of the PV system (Table 2.6).

Table 2.6: Cd emission scenarios for CdTe PV in 2025 and 2050.

Year and scenario	Global Cd emissions to air due to CdTe PV (kg/year)	As relative to current Cd emissions to air in EU-27 (%)	Global Cd emissions to water due to CdTe PV (kg/year)	As relative to current Cd emissions to water in EU-27 (%)
2008 'Base year'	0.8	0.0002	2.0	0.004
2025 'Pessimistic'	17	0.0043	40	0.07
2025 'Reference'	130	0.033	310	0.56
2025 'Optimistic'	170	0.043	400	0.72
2050 'Pessimistic'	100	0.025	240	0.42
2050 'Reference'	320	0.080	760	1.4
2050 'Optimistic'	350	0.088	840	1.5

The conclusion were, even under the largest growth scenario of 1TWp of installed CdTe PV power in 2050, the related Cd emissions to water and air, would be lower by at least two and three orders-of- magnitude than the present yearly Cd emissions within the EU-27 alone. It is also noteworthy that whenever CdTe PV specifically replaces coal in power generation, it lowers by 100–360 times the associated Cd emissions to air. The author's prospective life cycle analysis suggests that a large growth in the CdTe PV sector has the potential to actually reduce, rather than increase, overall global cadmium-related environmental pollution.

Overall, the effort in this review has been to have an India centric study whereby a comprehensive analysis of all the issues related to Cd and other toxic materials involved in CdTe manufacturing and CdTe PV systems were examined carefully under the conditions prevailing in the country. The review studies already conducted in other countries (e.g., [32]), can give the methodology to be followed and the conclusions can be indicative of what one may expect from the Indian study. However, under the current project the issue that has been examined is if there is any cause of concern if CdTe PV systems are deployed in India in large numbers. Note that the module recycle program is available to Indian systems as part of First Solar's international program.

3. Conclusions

The project undertaken by us has two main questions that were probed:

(i) Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product (including recycling)?

First Solar's production facility has all the required protection and safety features required to meet any unexpected situations arising from presence of Cd compounds in the work place. The project team's visit to First Solar Kulim (Malaysia) plant was an important step in understanding the processes involved in manufacturing CdTe modules and also the EHS practices being followed by the company. It was observed that the practices followed had proper control applied to the process steps and the possibility of release of any hazardous materials during manufacturing is negligible. The EHS practices also ensure that any exposure to the workers can be detected very early.

It has also been well proven that the amount of Cd compounds in the modules is extremely small ($<0.1 g/W_P$) and is well protected between glass sheets. Therefore there is hardly any possibility of Cd release during normal usage. Even under extreme situations like fire and leaching from broken modules, the models show that even if all the Cd compound was to be released, Cd concentrations within the near vicinity to the CdTe PV system are below human health screening levels [7, 22, 30]. That the Cd will get enclosed inside the molten glass is also to be noted [6]. The production facility also includes a dedicated recycling process to take care of end of life / scrap modules either from the production facility or from the field. The high recovery of the useful material will contribute to reconstruction of the cell components in order to mitigate the material availability issue.

(ii) What are the overall life cycle impacts of the large-scale deployment of CdTe PV systems on the environment, public health, and public safety, taking into account other energy alternatives?

Fthenakis et al. [5] reported after life-cycle-emissions analysis, that photovoltaic systems have emissions of about 17 to 39 g of CO_2e/kWh, when compared to the 500 to 1100 g of CO_2 e /kWh from the fossil-fuel plants, with CdTe PV having the smallest carbon footprint and fastest energy payback period among PV technologies. CdTe PV modules have about half the GHG emissions of crystalline Si. It can be concluded that PV systems, particularly using the CdTe have significant potential to mitigate global warming.

Current power generation technologies using coal have a large amount of Cd emitted in the environment in an uncontrolled manner, with the amount far exceeding the expected emission from CdTe modules even under exceptional conditions (e.g., fire). Even the dominant PV technologies based on Si solar cells have larger life cycle Cd emissions due to the embodied energy being larger for these devices [5]. Life cycle analysis also suggests that a large growth in the CdTe PV sector has the potential to actually reduce, rather than increase, overall global cadmium-related environmental pollution [31].

The CdTe PV recycling technology is designed to recover valuable raw materials, maximize the amount of material recycled, and minimize the environmental impacts. As an example of the importance of end-of-life management, one-third of the world's copper is currently found in landfills, rather than being incorporated in useful applications [23]. Recycling will save raw materials to a large extent, chemical byproducts will be reduced, and conservation of energy/electricity will be achieved.

4. Further Research

In all these studies, discussions and conclusions that we have arrived at, we have accepted, totally, the claim by First Solar that their supplier of the Cd compounds, maintains the strictest compliance to environmental, safety and occupational health norms and regulations. However, we have not independently verified this claim, since this was beyond the scope of the project. It is to be noted that the supply chain partner that produces and supplies Cd compounds to First Solar also manages the reprocessing of recycled semiconductor material back to semiconductor grade CdTe with suitable controls, and implements the electronic industry code of conduct (EICC) which addresses standards of performance in the areas of labor, health and safety, the environment, management systems, and ethics.

The pre-funded module collection and recycling program put in place by First Solar needs to be appreciated and should be promoted as good practice in the PV sector for all technologies. Looking at the implementation issues, especially in the Indian context, small volume users may not be opting for the module collection recycling program, even if it comes free of cost. In order to facilitate collection and recycling, we put forward the argument that since each and every CdTe PV panel manufactured by First Solar has a unique, bar-coded identification number associated with it, it should not be difficult for First Solar to keep a cradle to grave/cradle monitoring and documentation of each and every module and its ultimate fate in the recycle loop. Such initiatives are necessary where the wrong-doing of one (even out of ignorance) has the potential to cause harm to many. It should also be noted that First Solar focuses on large volume utility-scale (not small volume) PV applications and the prefunded collection and recycling program makes it the lowest cost end-of-life option. Also in order to maximize end-of-life collection and recycling rates of PV solar modules, a public policy discussion is needed on how end-of-life PV module recycling can be best ensured (e.g., through permitting requirements and/or mandatory take back legislation). This policy discussion is needed because mandatory recycling can only be accomplished through regulation.

One will like to point out that all the studies related to CdTe modules have been conducted in Europe or in the U.S. Since the environmental conditions and policies regarding waste disposal vary in Indian context, the same conclusions may not be directly drawn from the reported literature. An India centric study on PV waste disposal options taking into account the situations prevailing in India could be a welcome idea. Maybe recycling will be done in India in near future; in that case one needs to take a careful look into the existing recycling programme and then draw conclusions about a model for end-of-life recycling in Indian recycling plants.

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