First Solar CdTe Photovoltaic Technology: Environmental, Health and Safety Assessment

Final Report

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PHOTOVOLTAIC SOLAR ENERGY DEPARTMENT

NATIONAL RENEWABLE ENERGY CENTRE (CENER)

ENERGY AND CLIMATE CHANGE AREA

FUNDACIÓN CHILE

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1.- EXECUTIVE SUMMARY

1.1.- OBJECT

The object of the work is to evaluate, from an independent point of view, the environmental, health and safety (EHS) aspects of CdTe-based PV modules regarding process technology and modules working period in the field, in the context of First Solar's initiation of operations in Chile and South America.

The independent peer review undertook in the present work has been performed by CENER and Fundación Chile in a joint project.

1.2.- SCOPE

This report analyzes First Solar's process technology, beginning with the study of the raw materials, the manufacturing and recycling processes, including the analysis of the process routing, the materials modification steps and the in-line safety controls. A study of treatment and disposal of by-products will be carried out. Also, life cycle aspects of First Solar's CdTe PV technology will be analyzed, including energy payback time, greenhouse gas emissions, atmospheric Cd emissions, tellurium availability, water use, impacts on biodiversity, land use, and external costs. Finally, an evaluation of safety aspects during the CdTe modules working period will be done, taking into account four main aspects: breakage, fire, slow degradation and end-of-life.

1.3.- METHODOLOGY

The methodology applied for working out the present report is based on a careful data mining and general search of information. Articles and reports, published by recognized scientists, international agencies and research and development institutions have been used as well as information provided by First Solar on their specific technology and management systems. This information is then compared and subjected to a critical analysis, based on the experience and know-how regarding PV technology existing within the PV Department of CENER and the Energy and Climate Change Area of Fundación Chile.

1.4.- CONCLUSIONS

After having conducted a detailed analysis of the most recent scientific articles and the specific internal information provided by First Solar related to the CdTe technology for the manufacturing of PV modules the drawn conclusions are summarized in the following paragraphs:

EH&S aspects of First Solar CdTe process technology

- Cadmium is obtained as a by-product of smelting of zinc, lead and copper, therefore, its production does not depend on the PV market demand. First Solar's PV modules, by converting the Cadmium into the stable compound CdTe, provide a beneficial and safe usage for this heavy metal considered a pollutant that is otherwise stored for future use, or disposed of in landfills as hazardous waste.
- First Solar manufacturing facilities are equipped with the state-of-the-art technology to control cadmium emissions into the indoor and outdoor air. First Solar manufacturing facilities are also provided with the required technology to treat waste effluents for all manufacturing operations, including modules recycling. Current cadmium air emission and wastewater effluents are well below the local regulations threshold limits. All First Solar manufacturing facilities are ISO 9001:2008, ISO 140001:2004, and OHSAS 18001:2007 certified.
- First Solar's Industrial Hygiene Management Program for cadmium management includes air sampling for personal, area and equipment, medical surveillance for all affected employees including blood and urine testing, administrative controls with written programs and policies, personal protective equipment protocols, housekeeping and factory cleanliness activities and employee training. In this respect, a globally comparable air sampling strategy is completed quarterly, from which it can be concluded that the Cadmium level in air is always well below Occupational Exposure Limits. As complementary activities to air monitoring, First Solar also performs bio-monitoring tests. As a result of these bio-monitoring tests, Cd levels in blood and urine are demonstrated to be well below U.S. Occupational Health & Safety Administration criteria.

Life cycle aspects of First Solar CdTe PV modules: energy use and potential environmental impacts

- There is ample evidence that, from a life cycle perspective CdTe PV technology is a preferable option in environmental terms when compared to fossil fuels as well as to an extent, to other PV technologies, considering greenhouse gas emissions, energy payback time, water use, cadmium emissions and impacts on biodiversity.
- The high solar irradiation conditions of northern Chile result in an even better

environmental performance per unit of energy produced when compared to published studies. Energy payback time for CdTe PV systems installed in northern Chile is expected to range from 0.4 to 0.6 years, while greenhouse gas emissions are expected to be approximately 12 g CO_2eq/kWh.

- First Solar's CdTe PV technology shows a promising prospect to provide a low environmental impact energy source, both for Chile and globally, particularly when best practices are implemented regarding land use, biodiversity management and end-of-life collection and recycling of modules.
- On a total cost basis including private cost (LCOE) plus the addition of life cycle environmental cost and a performance cost related to variable generation, CdTe PV is competitive with fossil fuels such as coal and natural gas.

EH&S aspects of First Solar CdTe PV modules during working life

- Under normal operating conditions, First Solar CdTe PV modules do not generate any pollutant emissions at all, in contrast to the fossil fuel-burning energy sources.
- In the improbable case that a fire or breakage might occur, the emissions of cadmium to the air, water and soil have been proved, through scientific studies, to be negligible and do not represent a potential risk for human health nor for the environment.
- At the end-of-life, the risk of uncontrolled spreading of Cd is considered to be negligible at approved landfills depending on country regulation. Uncontrolled dumping of CdTe modules will provide greater environmental risks compared with controlled disposal. Responsible disposal is important for all PV technologies as use of environmentally sensitive materials (e.g., Pb, Cd, and Se compounds) is common in the industry.

As a summary, concerning manufacturing operations, First Solar has continuously implemented outstanding policies, practice, procedures and management system in order to protect workers' health and safety. During normal operating conditions, First Solar's CdTe PV modules emit zero pollutants to the air, water and soil. In the exceptional case that an accident like fire or breakage occurs, the emission of cadmium has been proven to be negligible and do not represent a potential risk for human health nor for the environment. At the end-of-life, either CdTe PV modules recycling (recommended option when available) or their disposal at an approved landfill will ensure keeping the risk negligible.

2.- TECHNICAL REPORT

The concern about environmental pollution and global warming has been continuously growing in recent years. The production of electricity by means of fossil fuel-burning plants has caused health problems, acid rain, and has increased atmospheric carbon dioxide concentration as well as emissions of heavy metal particles. In order to reduce these emissions, the use of more sustainable ("green") energy sources began to be investigated and applied several years ago. In this respect, the European Commission has set an ambitious target of 20% of renewable energy sources in the European Union energy budget to be reached by 2020. Similarly in Chile, 20% of the energy generated has to be from renewable sources (wind, solar, geothermal, biomass, small hydro <20 MW) by year 2025.

Among the alternatives to fossil fuel power plants, nuclear power, solar power, geothermal power, wind power and hydroelectric power can be considered. Photovoltaic solar electricity has attracted an increasing interest in the past years. The possibility of obtaining electricity directly from the sun and its modularity has been the main reasons for that interest. Besides, Photovoltaic solar electricity causes no emissions during the working life and the sunlight supply is unlimited and guaranteed. On top of that, the recent increase in efficiency and cost reduction of PV modules has allowed the achievement of grid parity in some countries.

The initial PV cells were based on monocrystalline silicon wafers but silicon could also be deposited directly from gas phase onto a substrate for PV applications. Nevertheless, silicon is not the only semiconductor material that responds to sunlight for PV energy conversion. Other semiconductors have similar properties and thin film technologies have emerged as promising candidates.

The three main thin film technologies, as of today, are amorphous/microcrystalline silicon, cadmium telluride and copper indium diselenide (and derivatives) that share a number of common features as:

- The requirement of only small amounts of semiconductor material; the semiconductor film thickness is typically in the order of a few microns.
- They have long-term stability under outdoor conditions.
- They require minimal energy inputs compared to crystalline silicon based technology.
- They can be manufactured with a wide range of process technologies.

In the last two decades, great research and development efforts on thin film technologies have been done and the effort turned into reality the initial expectations for those technologies.

In the present study, First Solar's process technology has been analyzed, beginning with the analysis of the raw materials used, the manufacturing process has been also reviewed, including the analysis of the process routing, the materials modification steps, the recycling process and in line safety controls. To finish the analysis of the environmental aspects associated to the manufacturing process, a study of treatment and disposal of by-products has also been carried out.

Life cycle aspects of the CdTe technology used by First Solar have also been reviewed and compared with other electricity generation options. Aspects considered in this analysis include energy payback time, greenhouse gas emissions, atmospheric Cd emissions, tellurium availability, water use, impacts on biodiversity, land use, and external costs.

Finally, an evaluation of safety aspects during the CdTe modules working period has been done, taking into account four main aspects: breakage, fire, slow degradation and end-of-life.

First Solar has conducted since 2005 at least 9 Peer Review studies regarding their CdTe technology for the production of PV modules.

2.1.- ANALYSIS OF THE CdTe PROCESS TECHNOLOGY FOR PV MODULES

In this section First Solar's process technology for manufacturing PV modules will be analyzed, starting with the analysis of the raw materials used, evaluation of raw materials suppliers and their environmental policy. Next, First Solar's manufacturing and recycling processes will be reviewed, including the process routing, the materials modification steps and in line safety controls, with special emphasis on First Solar's own environmental health and safety programs. Finally, an analysis of the manufacturing by-products, their treatment and disposal procedures will be carried out.

2.1.1.- RAW MATERIALS AND SUPPLIERS ANALYSIS

With the aim of focusing the main EHS aspects of the CdTe thin film technology used by First Solar, some considerations about Cd, Te and CdTe (a synthetic material) regarding their physicochemical properties, natural occurrence and health and safety profile will be presented.

Cadmium is a heavy metal naturally present in the earth's crust, oceans and the environment. As many other heavy metals like lead, zinc, chromium, arsenic, cobalt, copper, tin, manganese, nickel and mercury, its usage in the electric and electronic industries is widely common. Metallic cadmium has a silver grey metallic color with a melting point of 321 ºC and a boiling point of 765 ºC.

Cadmium is found in the earth's crust in zinc ores, as cadmium sulfide, in a proportion of 0.0001% to 0.2%[1]. The most common separation method in mining is froth flotation that ends with a zinc mineral concentrate that is transferred to smelters/refiners to produce the primary

[1] International Cadmium Association, http://www.cadmium.org

metals. The electrolytic process is the most extended method to produce Zn; residues from that process together with dust and fumes produced by the pyrometallurgical processing of zinc and lead are the feed materials to obtain Cd. Cadmium production is driven by the Zn market demands and cadmium concentrate wastes need to be stored until some application requires their usage. China, Canada and the US are the biggest Zn producers.

Tellurium is a very rare semi-metal, extracted mainly as a by-product from the copper and lead ores. Copper anode slimes and lead refinery skimming are the main by-products used for tellurium extraction from copper and lead refineries[2].

Cadmium telluride, used for photovoltaic applications, is a synthetic black solid material obtained by the reaction of their parent elements Cd and Te, either in gas-phase or liquid-phase processes. CdTe is stable at atmospheric conditions with a melting point of 1041 ºC and evaporation at 1050 ºC[3], although sublimation occurs, CdTe vapor pressure is 0 at normal conditions and is only 2,5 torr (0,003 atm) at 800 ºC[4].CdTe has a low solubility in water (CdTe solubility product $9.5x10^{-35}$mol/L compared with Cd solubility product 2.3 mol/L) but is dissolved in oxidant and acidic media and it may decompose on exposure to atmospheric moisture being able to react with water and oxygen at elevated temperatures[4]. CdTe exhibits bioavailability properties that are approximately two orders of magnitude lower than the 100% bioavailability of $CdCl_2$[5]; this means that CdTe does not readily release the reactive ionic form of Cd (Cd^{2+}) upon contact with water or biological fluids.

On top of that, there are several studies which show that the toxicity and environmental mobility of CdTe is much lower than Cd and other Cd compounds:

- Acute inhalation and oral toxicity. The study from Zayed and Philippe[6] on rats, found that the median lethal concentration (LC50) and dose (LD50) to be more than 3 orders of magnitude higher than that of Cd
- Reproductive development sub-chronic oral toxicity studies. No detectable effect of CdTe on male or female rat reproduction at doses high enough to cause body weight gain reduction was found in the study carried out by Chapin[7].
- Mutagenicity. Bacterial reverse mutation assay (Ames test) was tested by Agh in 2010[8]

[2] V. Fthenakis, W. Wang, H. C. Kim, "Life cycle inventory of the production of metals used in photovoltaics", Renewable and Sustainable Energy Review, 13, 493-517, 2009
[3] P. Moskowitz, N. Bernhole, V. M. Fthenakis, R. Pardi, "Environmental health and safety issues related to the production and use of cadmium telluride photovoltaic modules", Advance in Solar Energy, vol.10, Chapter 4, American Solar Energy Society, Boulder CO, 1990
[4] "DOE and BNL Nomination of CdTe to the NTP", April 11, 2003
[5] T. Brouwers, "Bio-elution test on cadmium telluride", ECTX Consultant, Liège, Belgium
[6] P. Zayed, S. Philippe, "Acute oral inhalation toxicities in rats with cadmium telluride", International Journal of Toxicology, Vol 28, Nº 4, 259-265, 2009
[7] R. E. Chapin, M. W. Harris, J. D. Allen, E. A. Haskins, S. M. Ward, R. E. Wilson, B. J. Davis, B. J. Collins and A. C. Lockhart, "The systematic and reproductive toxicities of copper indium diselenide, copper gallium diselenide and cadmium telluride in rats", Understanding and managing health and environmental risks of CIS, CGS and CdTe photovoltaic module production and use: A workshop (BNL-61480), eds. P. D. Moskowitz, K. Zweibel and M. P. DePhilips, Brookhaven National Laboratory, (Chapter 2), 1994
[8] Agh, "The testing of cadmium telluride with bacterial reverse mutation assay", Lab Research Ltd, Veszprém, Hungary, 2010

and no mutagenic activity was found which compares to positive mutagenicity results for Cd

- Acute aquatic toxicity. Studied by Agh in 2011[9], no toxic effect at aquatic saturation on fish was found.

These results in comparison with Cd are summarized in Figure 1.

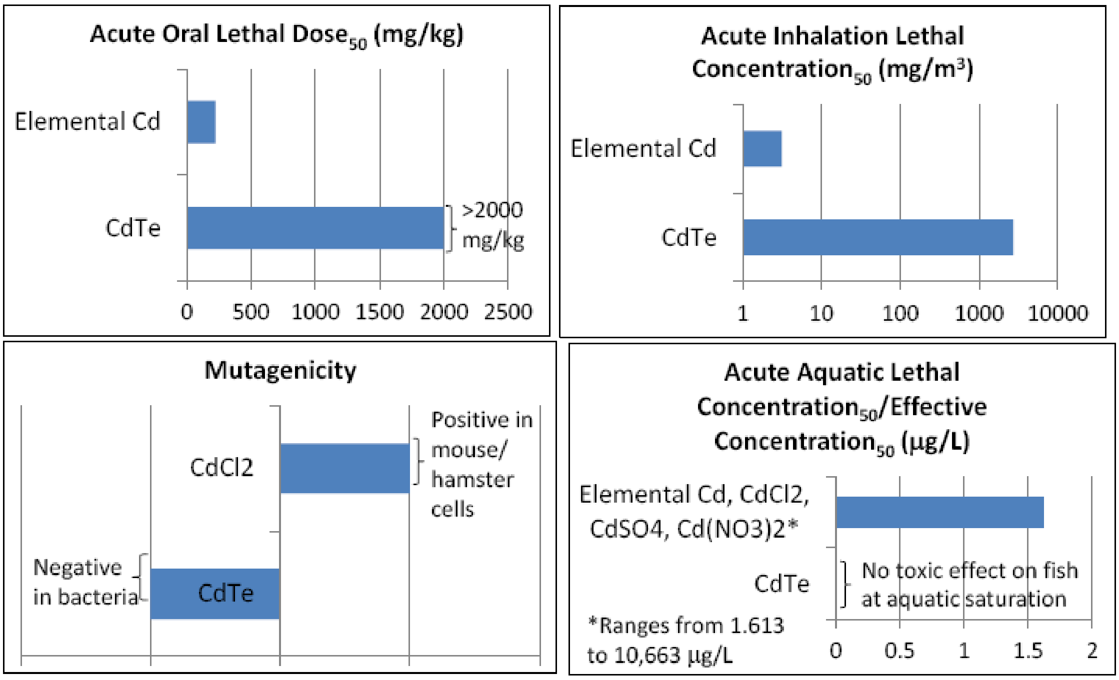


Figure 1 Comparative toxicity between Cd and CdTe[10]

In this regard, the European Chemicals Agency (ECHA) has been notified that CdTe will be no longer classified as harmful if ingested nor in contact with skin, and the toxicity classification to aquatic life has been reduced[11] (The original document has not been reviewed).

Nevertheless, CdTe powder production implies Cd and Te usage, and, Cd and all cadmium compounds are still classified by OSHA at the same level of hazardousness.

CdTe is a semiconductor compound with a direct band gap of 1.5 eV, nearly ideal for terrestrial energy conversion. Its high absorption coefficient and the wide variety of low cost manufacture techniques have made cadmium telluride one of the most promising materials to scale-up photovoltaic energy production.

First Solar's modules manufacturing technology uses, as starting raw material, a black CdTe powder. As it has been described before, CdTe is produced from the reaction of Cd and Te by

[9]Agh, "Acute toxicity test with cadmium telluride on zebrafish", Lab Research Ltd, Veszprém, Hungary, 2011
[10] S. Kaczmar, "Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics", Society of Environmental Toxicology and Chemistry (SETAC) North America, 32nd Annual Meeting, 2011
[11] M. Held, C. Hagendorf, J. Bagdhn and R, Wehrspohn. Scientific Comment of Fraunhofer to Life Cycle Assessement of CdTe Photovoltaic, http://www.csp.fraunhofer.de/presse-und-veranstaltungen/details/id/47, 2012

different techniques. Depending on the technology used by the producers, the precursor nature and quality degree may differ. First Solar purchases the CdTe compound from its suppliers.

The identity of the suppliers is considered confidential information by First Solar and no information has been disclosed in that respect. Nevertheless, First Solar has a policy that encourages its suppliers to be certified to the same ISO (ISO 9001: Quality Management System and ISO 14001: Environmental Management System) standards it is certified to. In addition, First Solar suppliers are asked to comply with Electronic Industry Citizenship Coalition Code of Conduct regarding Environment, Ethics, Health and Safety, Labor and Management systems.

Indeed, for all cadmium related suppliers, including products and services like waste disposal facilities, First Solar undergoes environmental audits performed by themselves or by a third party. If needed, a corrective action plan is requested to the supplier and a follow up activity is carried out until all issues are completed. Furthermore, First Solar shares EHS best practices with their suppliers to help them achieve a higher performance profile on environmental, health and safety aspects.

During the Perrysburg plant visit, First Solar provided new information and documentation regarding their sustainability strategy. In that regard, a supplier sustainability assessment scorecard has been shared.

Regarding the EHS aspects, no further analysis in the supply chain was performed due to the lack of information.

2.1.2.- MANUFACTURING PROCESS

In CdTe PV module manufacturing, three main process sequences are used: the first one corresponds to semiconductor deposition, where the semiconductor material, responsible for the sunlight conversion into electricity, is deposited; secondly, PV cell formation; and thirdly, the final module assembly and test is performed.

First Solar's CdTe PV cell manufacturing technology is based on the sublimation property of CdTe. As the material is heated, CdTe sublimes to yield gaseous Cd and Te_2 molecules that are re-deposited onto the substrate.

The first process sequence starts with the deposition onto a glass substrate of a thin tin oxide layer that serves as a transparent and conductive contact (TCO). Note that the TCO layer is applied to the glass by the glass supplier. Then, very thin CdS (window) layers followed by a CdTe (absorber) thin layer are deposited. The CdS and CdTe layers are deposited using powders of the same materials by means of a vapor deposition technique. Next, $CdCl_2$ is sprayed and a thermal treatment is applied. This process is performed in order to re-crystallize the structure and improve the electronic properties of the device. Note that $CdCl_2$ is washed off the module after the recrystallization process is complete. Finally, a metal layer, using sputtering techniques, is deposited to create the back contact.

In the second sequence, the individual photovoltaic cells are interconnected in series using a laser scribe technology, followed by the third sequence which includes a lamination process where an intermediate polymeric adhesive and a glass plate are placed and thermally sealed together with the glass substrate.

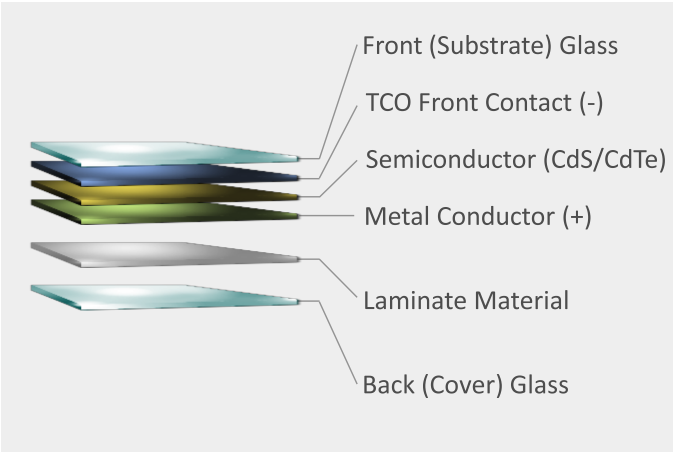


Figure 2 Schematic representation of First Solar module architecture[12]

As can be seen from Figure 2, at the end of the process sequence described above, the final module is formed of a series connected CdTe PV cells with a film thickness less than 10 microns and about 7 g/m^2 of cadmium content, encapsulated, insulated with solar edge tape, and sealed between two glass plates of about 3 mm thick each.

First Solar's CdTe core process technology is based on the sublimation property of CdTe. At certain specific pressure and temperature conditions, CdTe decomposes in its parent compounds Cd and Te. Those species in gaseous phase are deposited onto the surface of a substrate in the form of a thin CdTe layer with semiconductor properties. First Solar process uses a high-rate vapor deposition technology that can deposit the thin semiconductor layer for the PV module in less than 40 seconds.

First Solar modules manufacturing process involves the following main steps:

[12] Sinha, P., "Life cycle materials and water management for CdTe photovoltaics". Solar Energy Materials & Solar Cells, 119, 271-275,2013

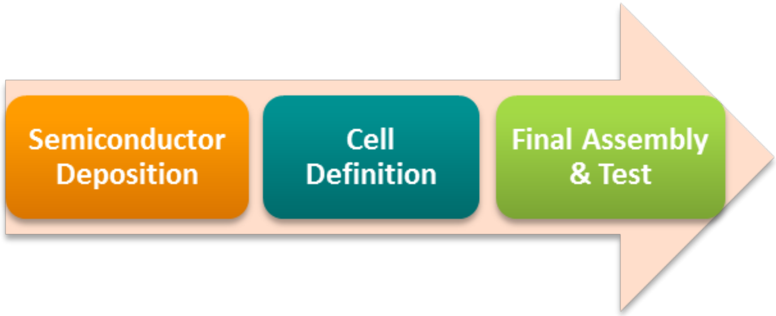


Figure 3 First Solar's manufacturing process

From the chemistry involved in the above process sequence, it can be extracted that Cd, Te, and/or CdTe are present either in gas-phase (dust and fumes) or dissolved in water, in a few of the manufacturing (operation and maintenance) steps.

- Steps from 1 and 2 might have Cd, Te and/or CdTe coming from the process itself, from the maintenance operations and from the scrap produced in the process. It should be noted that First Solar utilizes HEPA filtration systems to control emissions to well within regulatory standards.
- Step 3 has the possibility of existence of those materials coming from the scrap modules.

2.1.3.- RECYCLING PROCESS

First Solar has installed and put in operation commercial scale recycling facilities at each First Solar manufacturing location (U.S., Germany, and Malaysia). At these recycling facilities manufacturing scrap, modules under guarantee and end-of-life modules are processed. In the frame of a continuous improvement recycling program, First Solar has developed a version 2 of its original recycling process. The main process steps of First Solar's module recycling program version 2 are shown in Figure 4. The main improvement of version 2 is the use of static leach column reactor versus the rotary leach drum reactor. This solution provides the advantage of being easily expandable and the reduction in maintenance cost.

According to First Solar's recycling technology information, up to approximately 90% of the module weight is recovered, most of it being glass that can be used in new glass products. The estimated recovery of Cd and Te is up to approximately 95%. This unrefined semiconductor material is packaged for further processing by a third party recycling partner to create semiconductor material for use in new modules. The material that cannot be recovered is disposed of in accordance with waste disposal requirements.

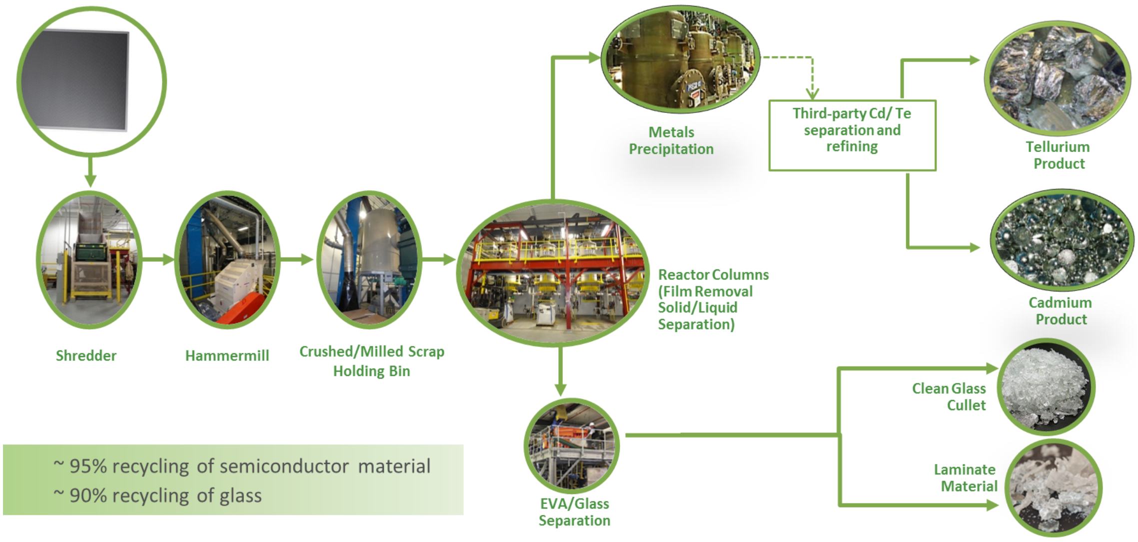


Figure 4 First Solar's module recycling technology version 2

The recycling process begins with the modules being reduced in a two step process. In a first step a shredder breaks the module into pieces, while step two makes use of a hammermill to crush the glass further into pieces of about 4 mm and 5 mm size, which are small enough to ensure the lamination bond is broken. Next the semiconductor films are removed by the addition of acid and hydrogen peroxide in a slowly rotating stainless steel drum. After that the drum is slowly emptied into a classifier where glass materials are separated from liquids, and a rotating screw conveys the glass up leaving the liquid behind.

The metal-rich liquid is pumped to the precipitation unit, where the metal compounds are precipitated in three stages at increasing pH. Then, the precipitated materials are concentrated in a thickening tank, and the resulting metals-rich filter cake is packaged for processing by a third party. With regard to the glass material, a vibrating screen separates the glass from the larger pieces of laminate material. Following, the glass in rinsed to remove any residual semiconductor films that may remain on the glass.

Through December 2012, approximately 48,000 metric tons of manufacturing scrap, warranty returns, and pre-mature end-of-life modules have been recycled at First Solar facilities worldwide.

Modules recycling capability is included in all First Solar's facilities as a standard production process, therefore, the same health and safety protocols used in the modules manufacturing operations are implemented to protect workers from the CdTe dust produced in the recycling processes.

2.1.4.- ENVIRONMENTAL HEALTH AND SAFETY POLICIES

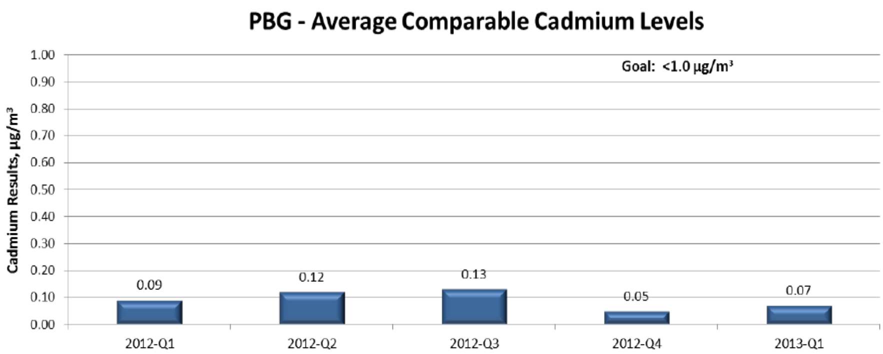
To prevent any EHS risks, First Solar has implemented continuous and effective control of the Cd indoor air concentrations, air emission levels and wastes concentrations. This control is also included during all maintenance operations.

First Solar has shared with CENER an extensive documentation dossier about their EHS procedures and policies as well as current emission data. These data have been deeply analyzed and are summarized below.

First Solar has a world-class design and operation system to control cadmium emissions to the indoor air and to the environment in all their manufacturing facilities. All process equipment involving cadmium is connected and managed by a High Efficiency Particulate Air(HEPA) filter control system that provides 99.97% capture efficiency for particles above 0.1 micron size. Every filter installed is tested using the strictest monitoring standard available (poly-alpha-olefin aerosol) to ensure capture efficiency. Even more, First Solar tests every ventilation system (not just the HEPA filters) to ensure the entire system integrity and has put in place an ongoing monitoring system that includes flow rates, efficiency and pressure drop monitoring for an extensive engineering control. On March 2009, the BGAI Institute for Worker Safety performed an evaluation of the air system and they concluded that "*it is recommended that the methods used by First Solar Manufacturing are recognized as being equivalent to those recognized by the professional associations…Furthermore, the monitoring of the workplace is exemplary".*

First Solar's Industrial Hygiene Management Program for cadmium management includes air sampling for personal, area and equipment, medical surveillance for all affected employees including blood and urine testing, administrative controls with written programs and policies, personal protective equipment protocols, housekeeping and factory cleanliness activities and employee training. In this respect, a globally comparable air sampling strategy is completed quarterly.

In Figure 5, the Perrysburg (PBG; U.S.) factory and Kulim (KLM; Malaysia) factory wide average Cd levels from Q1 2012 until Q1 2013 are shown.



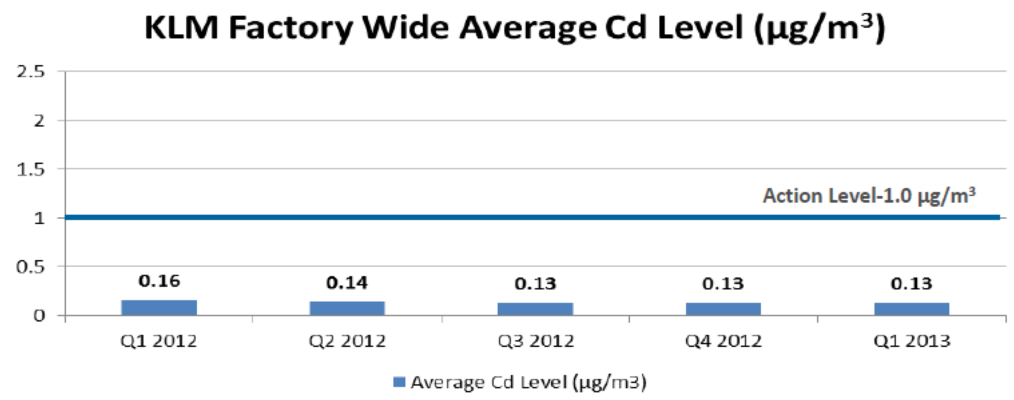


Figure 5 Perrysburg (U.S.) and Kulim (Malaysia) factories average Cd level ($\mu g/m^3$)

The action level of 1 $\mu g/m^3$ of Cd represent the level at which air monitoring will be more frequent and engineering controls evaluated.

In Figure 6 the personal exposure, divided by job function, sampling results from Q1 2012 until Q1 2013 can be found. This parameter is also measured through the plant on quarterly basis. The OEL (Occupational Exposure Limit) level represents the level to which an employee may be exposed for a given time without respiratory protection or engineering controls. The OEL levels for 8 and 12 hours in Malaysia are 10 $\mu g/m^3$ and 5 $\mu g/m^3$, respectively, while First Solar has established its own more severe OEL limits of 5 $\mu g/m^3$ and 2.5 $\mu g/m^3$, for 8 and 12 hours, respectively. As can be appreciated from this figure, the Cd level is always well below action level as well as OEL.

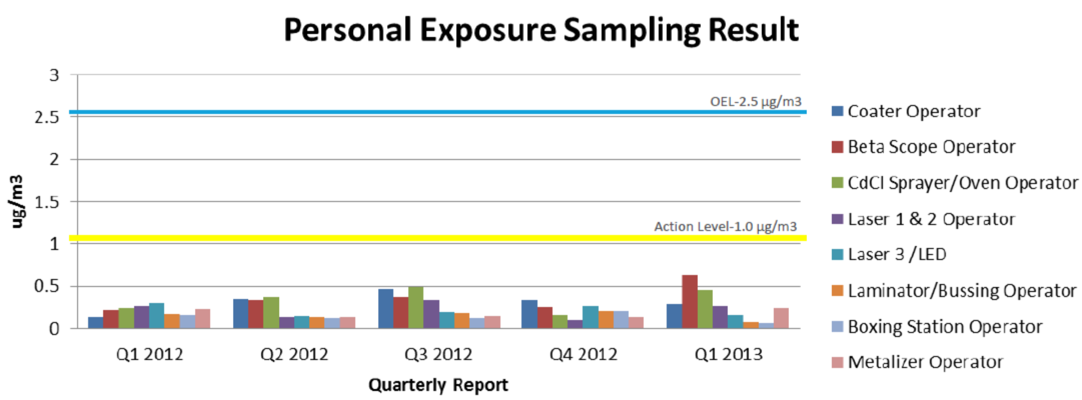


Figure 6 Personal exposure sampling ($\mu g/m^3$) by job function performed quarterly

As complementary activities to air monitoring, First Solar also performs bio-monitoring tests, which are necessary for identifying preventive interventions and also demonstrate that safety programs are effective. In Figure 7 and Figure 8 the mean Cd levels in blood and urine measured at the Perrysburg (U.S.) and Kulim (Malaysia) factories respectively are shown together with the OSHA limits. As can be appreciated from these figures Cd levels in both factories are well below OSHA criteria. The dotted line at 0.5 shows the limit of detection.

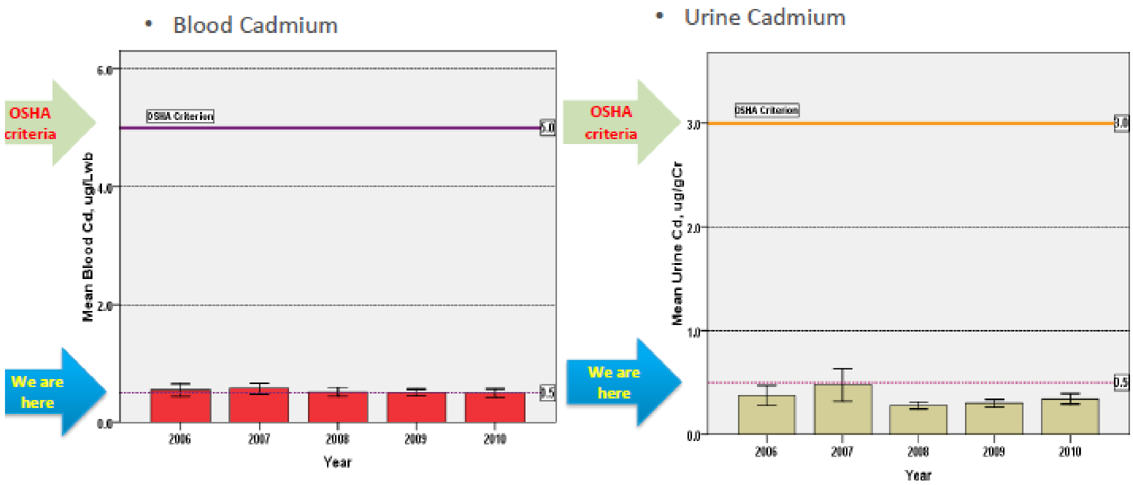


Figure 7 Perrysburg (U.S) factory mean Cd levels in blood and urine compared to OSHA biological limit

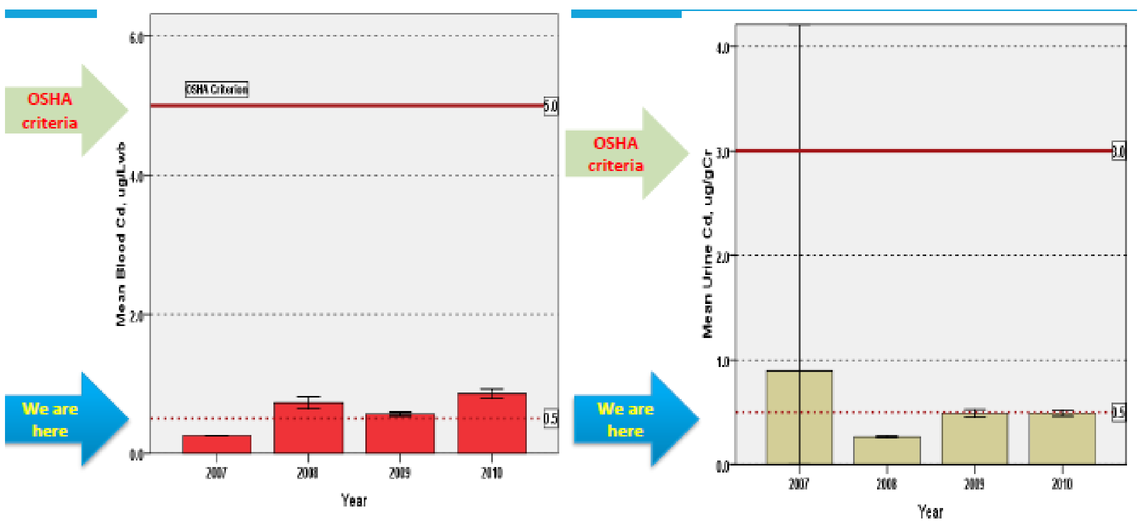


Figure 8 Kulim (Malaysia) factory mean Cd levels in blood and urine compared to OSHA biological limit

Besides, the company has carried out a comparison of annual Cd levels before and after being employed at First Solar, showing that there is statistically no significant difference between pre-employment and employment in the Cd levels[13].

First Solar's medical surveillance is reviewed by independent occupational physicians and results are shared with the employees. In the last review performed in 2012 by Dr. Michael L. Fischman[13], he concluded that "*This … study strongly suggests that there has been no observable impact of work around Cd at First Solar on biological monitoring results based upon*

[13] Draft Biomonitoring Report, Michael L. Fischman, M.D. September 25, 2012

several approaches". Before this study, other medical investigations provided similar results (e. g. Dr. Fahrang Akbar in 2009).

First Solar has a strong commitment on health and safety to ensure a safe workplace for all employees. In this respect, they have in-staff experts on all the disciplines related to EHS aspects. Regarding the strategy for new facilities, their implementation is based on the "copy smart" concept including policies, practices and management systems.

All First Solar manufacturing facilities have received the following third party certifications for effective management systems:

- ISO 9001:2008 Quality (Mission statement, quality objectives, system and product audits, internal reliability test labs, continuous improvement)
- ISO 14001:2004 Environmental (Waste recycling, pollution prevention, and wastewater treatment)
- OHSAS 18001:2007 Occupational Health and Safety (Comprehensive safety and health programs to promote "Safety First"; active participation through safety teams)

First Solar is very active in developing and improving safety programs, encouraging the participation of the inline staff as well as of the management personnel.

2.1.5.- ANALYSIS OF THE MANUFACTURING BY-PRODUCTS

Dust, fumes and wastewater containing cadmium, tellurium and cadmium telluride are the main manufacturing by-products generated during the modules fabrication and recycling processes. The by-products treatment leads to three different types of wastes: air exhausted to the environment, wastewater and solid wastes.

Using a cadmium mass balance to quantify the mass flows of cadmium in the manufacturing processes it has been shown that 66% of total cadmium is used in CdTe PV modules, 25% corresponds to recycled modules, 9% is disposed of as unspecified waste, 0.02% is emitted to water and 0.0001% corresponds to air emissions[14].

2.1.5.1.- Air emissions

As has been described earlier, First Solar has a state-of-the-art HEPA filter control system that leads only to a 0.0001% of the incoming cadmium emitted into the air; indeed, the exhausted treated air is injected into the manufacturing facility ventilation system. First Solar estimates in less than 6 g/yr the total cadmium emissions into the air for a 100 MW/yr facility.

[14] First Solar data

According to data from 2010 released by First Solar, Cd emissions to air in US in form of CdTe accounted for 5.34×10^{-9} kg per m^2 module[15]. Air emissions meet the permitted emission limits. With regard to the Kulim factory in Malaysia, a measurement carried out by NM Laboratory Sdn. Bhd. disclosed that: the air impurities and solid particles concentration emitted from the chimneys of Building KLM 5 on the 05th of March 2013 did not exceed the limit as stated in the Standard "C" limit in the Environmental Quality (Clean Air), Regulation 1978, Part V, No 27 and No 25.

2.1.5.2.- Water emissions

First Solar's wastewater treatment process flow includes operations like metals precipitation, filtration and ion exchange polishing (see Figure 9). On top of that, there is a continuous checking of the Cd content of the water that is going to be discharged and, if it is out of specifications, the wastewater is re-circulated again to the wastewater treatment systems. These processes reduce Cd levels in wastewater to less than 20 ppb (typical value is 10 ppb) at First Solar's Malaysia facility.

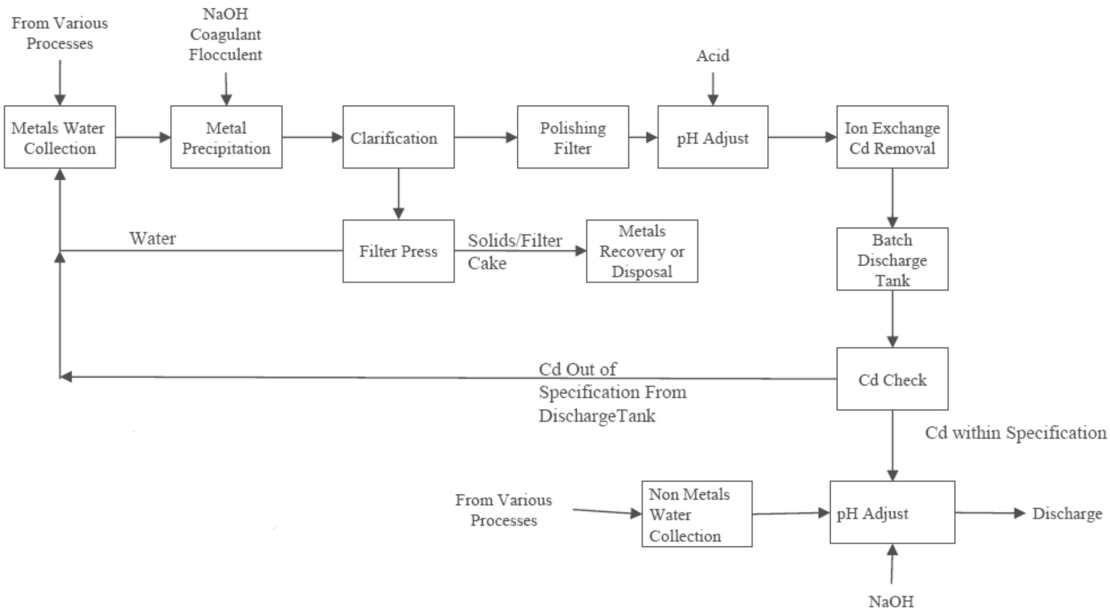


Figure 9 Wastewater treatment process flow diagram

Regarding wastewater, First Solar cadmium mass balance indicates that less than 0.02% of the total incoming cadmium is released into water.

According to data from 2010 released by First Solar, Cd emissions to water in form of Cd^{2+} accounted for 4.43×10^{-7} kg per m^2 module[15]. 2012 data from Kulim facility confirmed that the amount of Cd released in wastewater per MWp was<1.4 g. In this regard, data of 2012 performance of the water waste treatment plant at First Solar Malaysia and Perrysburg

[15] N. Jungbluth, M. Stucki, K. Fluri, "Life cycle inventories of photovoltaics", 2012

concluded that the Cd concentration discharged in water did not exceed the regulatory final discharge limits[16].

2.1.5.3.- Other solid wastes

During manufacturing operations, other solid wastes are also generated including used HEPA filters, waste from maintenance operations, ion exchange resins, etc. These wastes represent 9% of the total incoming cadmium. HEPA filters of both factory locations are sent to third parties for disposal as hazardous waste. Ion exchange resins stay within the system because they are regenerated and used again.

Additionally, First Solar is developing the recycling of laser dust with other third parties in Perrysburg that, according to First Solar information, are ISO 9001 and 14001 certified.

No further EHS analysis in the supply chain was performed due to the lack of information of the third parties.

2.1.5.4.- Sustainability

First Solar has established a cross-functional Sustainability Steering Committee to execute on Sustainability initiatives. These initiatives focus on the reduction of carbon footprint and energy consumption, supplier management, community involvement, responsible land use and overall business performance.

Some metrics have been disclosed which show the efforts that First Solar has made in order to reduce the amount of by-products disposed by its factories:

- Water consumption per watt produced decreased by more than 13% from 2009 (1.9 L/Watt produced) to 2012 (1.64 L/Watt produced) through water conservation and reuse projects and improved module efficiency.
- Waste generation per watt produced has also decreased by approximately 50% from 2009 (35.1 g/watt produced) to 2012 (19.1 g/watt produced) as a result of wastewater treatment process enhancements.

In general, overall of the total material First Solar sends off-site, 83% is sent for beneficial reuse and not to landfill. These improvements have been accompanied by a reduction of the energy consumption per watt produced and of the greenhouse gas emissions so the environmental footprint of First Solar is progressing towards a greener profile.

Most importantly, the continuous improvement of First Solar's technology has driven a significant increase of their module efficiencies in recent years. Consequently, it is expected that

[16] First Solar documentation

the evolution of First Solar modules efficiencies in the near future will continue (see Figure 10). This upgrade, apart from benefiting the competiveness of CdTe PV modules, will improve the sustainability metrics mentioned above.

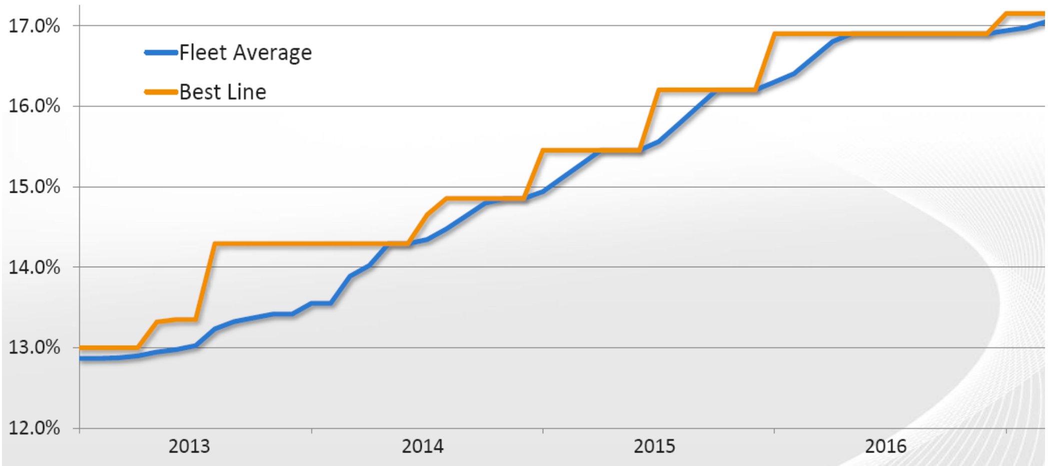


Figure 10 First Solar CdTe module efficiencies roadmap

2.2.- LIFE CYCLE ASPECTS OF FIRST SOLAR'S CdTe PV MODULES

Life cycle aspects of the CdTe technology used by First Solar will be reviewed in this section, and put into context by comparing them with other electricity generation options. Aspects considered in this analysis include energy payback time, greenhouse gas emissions, atmospheric Cd emissions, tellurium availability, water use, impacts on biodiversity, land use, and external costs.

2.2.1.- ENERGY PAYBACK TIME (EPBT)

Energy Payback Time is one of the most widely used indicators to assess the energy performance of PV systems[17]. It is defined as "the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself. It is calculated as follows[18]:

$$EPBT = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{\left(E_{agen} / \eta_G \right) - E_{O\&M}}$$

Where the different terms are defined as:

E_{mat}	Primary energy demand to produce materials comprising PV system
E_{manuf}	Primary energy demand to manufacture PV system
E_{trans}	Primary energy demand to transport materials used during the life cycle
E_{inst}	Primary energy demand to install the system
E_{EOL}	Primary energy demand for end-of-life management
E_{agen}	Annual electricity generation
$E_{O\&M}$	Annual primary energy demand for operation and maintenance
η_G	Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

Peng et al. reviewed published EPBTs for different PV systems. Figure 11 shows published EPBT calculations from that study, standardizing the irradiation at 1700 kWh/m^2/yr. For CdTe, EPBT was found to range from 0.8 to 2.1 years, constituting the lower range between the studied technologies.

[17] Peng, J., Lu, L., & Yang, H. 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255-274.
[18] Fthenakis, V., et al. 2011.Methodology guidelines on life cycle assessment of photovoltaic electricity. IEA PVPS Task 12.

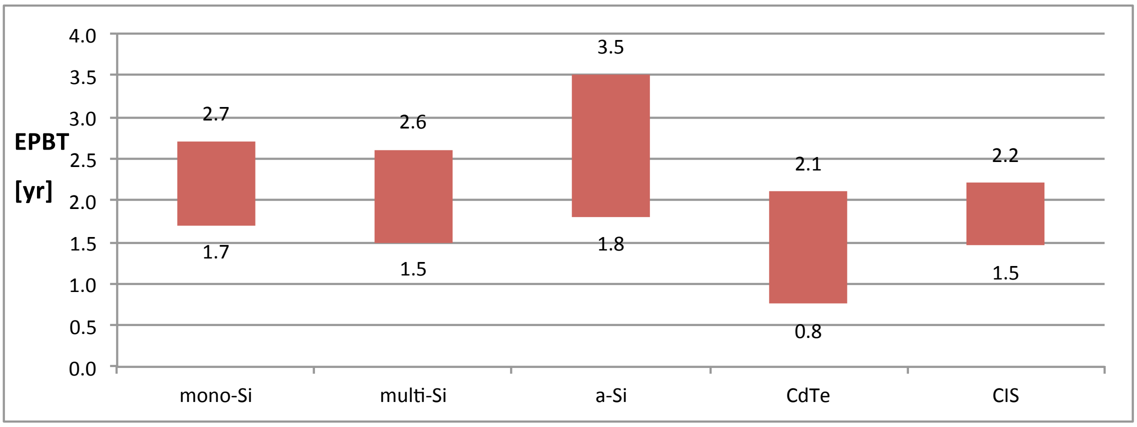


Figure 11 Energy Payback Time [yr] for different PV technologies. Irradiation standardized at 1700 kWh/m2/yr. Adapted from Peng et al., 2013

EPBT was calculated for the deployment of First Solar's modules under the conditions of northern Chile for two different locations: Crucero and Carrera. The Crucero site would be connected to the Northern Interconnected Grid (SING), while the Carrera site would be connected to the Central Interconnected Grid (SIC).Table 1 shows the solar irradiation data considered for these locations. These were obtained from Universidad de Chile's geophysics department's Solar Explorer website, considering a 10 year average (2003-2012), which was consistent with direct on-site measurements made by First Solar during 2012 (2626 and 2540 kWh/m2/yr for Crucero and Carrera sites, respectively). Fixed-tilt plane-of array irradiation was estimated by using a default factor of 1.12.

	Crucero Site	Carrera Site	Source
Electricity Grid	SING	SIC	-
Global Horizontal Irradiation [kWh/m^2/yr]	2537	2533	U.de Chile, 2012[19]
Fixed-tilt Plane-of-array Irradiation [kWh/m^2/yr]	2841	2837	Using plane-of-array conversion factor of 1.12 [20]

Table 1 Radiation data for two possible locations in northern Chile.

Parameters considered for the calculation of EPBT are shown in Table 2. A cumulative energy demand (CED) value of 1270 MJ/m2 was used[21]. This value includes production of materials, module manufacturing, installation, ground-mount balance of system (BOS) and End-of-Life (EOL) recycling. A module efficiency of 12.7% was used, reported by First Solar to be the

[19]Universidad de Chile, 2012. Explorador solar. http://ernc.dgf.uchile.cl/Explorador/Solar2/
[20]First Solar, 2012. Technical report: Estimating Carbon Displacement by Solar Deployment.
[21]Held, M., & Ilg, R. 2011. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Progress in Photovoltaics: Research and Applications, 19(5), 614-626.

average performance for 2012. Finally, grid efficiencies were calculated for the SIC and SING grids. A grid efficiency of 29% was obtained for the SING grid, and 43% for the SIC grid. The main difference between them lies in the high fossil fuel consumption at SING electrical grid (98% of fossil fuel as primary energy) versus SIC electrical grid (52% of fossil fuel as primary energy). The details of their composition of both grids can be found in Appendix3.1.

Information	Value	Source
CdTe PV system CED [MJ/m^2][22]	1270	Held and Ilg, 2011
Efficiency Module [%]	12.7	First Solar (average 2012 performance)
Performance Ratio	0.8	Fthenakis et al., 2011
Lifetime (yr)	30	Held and Ilg, 2011
Degradation rate (%/yr)	0.7	Held and Ilg, 2011
SING grid efficiency (%)	29	This study
SIC grid efficiency (%)	43	This study

Table 2 Parameters used for EPBT calculation

As the prior information doesn't include transportation values (km and CED), distances from the nearest port of production to Antofagasta Terminal in ocean freight, from Antofagasta to installation point in truck and from Antofagasta Terminal to nearest EOL destination port were estimated. Table 3 shows the distances and EPBT relevant information.

Transport	Distance [km]	Vehicle	CED [MJ/m2]	Source
Solar Panel Delivery (Penang, Malaysia to Antofogasta Terminal, Chile)	19863	Ocean freight	55	Distance: Searates CED: Ecoinvent background process
End-of-life recycling (Antofogasta Terminal, Chile to Hamburg Terminal, Germany)	13586	Ocean freight	38	Distance: Searates CED: Ecoinvent background process
Solar Panel Delivery or EOL recycling (Antofogasta Terminal, Chile to Detroit Terminal, USA	11155	Ocean freight	31	Distance: Searates CED: Ecoinvent background process
Solar Panel Delivery or EOL recycling (Antofagasta terminal, Chile to Crucero, Chile)	217	Truck (EURO 3)	11	Distance: Google Maps CED: Ecoinvent background process
Solar Panel Deliver or EOL recycling (Antofagasta terminal, Chile to Carrera, Chile)	637	Truck (EURO 3)	33	Distance: Google Maps CED: Ecoinvent background process

22 Value includes production of materials, solar panel production, installation, BOS and End-of-Life (EOL) recycling. It does not include transport of panels from production point to installation point neither from installation point to EOL recycling.

Table 3 Transport distances and CED information

Table 4 shows the results for EPBT calculated for four modeled scenarios, considering different sources and end-of-life options. It can be seen that EPBT are lower than in the reviewed studies, owing to the high solar irradiation at the proposed sites in northern Chile. It can also be noted that the EPBT for a power plant connected to the SING grid is significantly shorter than for the SIC grid, due to the fact that it is displacing a higher proportion of fossil fuels. Finally, it can be observed that the distribution and collection of panels, which is often not accounted for in life cycle assessment studies, for these cases can account for up to 13% of the system's cumulative energy demand.

	Crucero (SING/Panel from MY/EOL GE)	**Crucero (SING/Panel from US/EOL US)**	**Carrera (SIC/Panel from MY/EOL GE)**	**Carrera (SIC/Panel from US/EOL US)**
Cradle to Recycling CED [MJ/m^2]	1386	1355	1430	1399
Irradation [kWh/m^2/yr]	2841	2841	2837	2837
EPBT [yr]	**0.39**	**0.38**	**0.60**	**0.59**

Table 4 EBPT (yr) for four modeled scenarios.

Figure 12 shows the previous results in comparison with different CdTe PV systems and irradiation described in the literature. Worst case scenarios are shown for each North-Chile location, being North-Chile1 Carrera and North-Chile2 Crucero. Details for the other studies are detailed in Appendix 3.2.

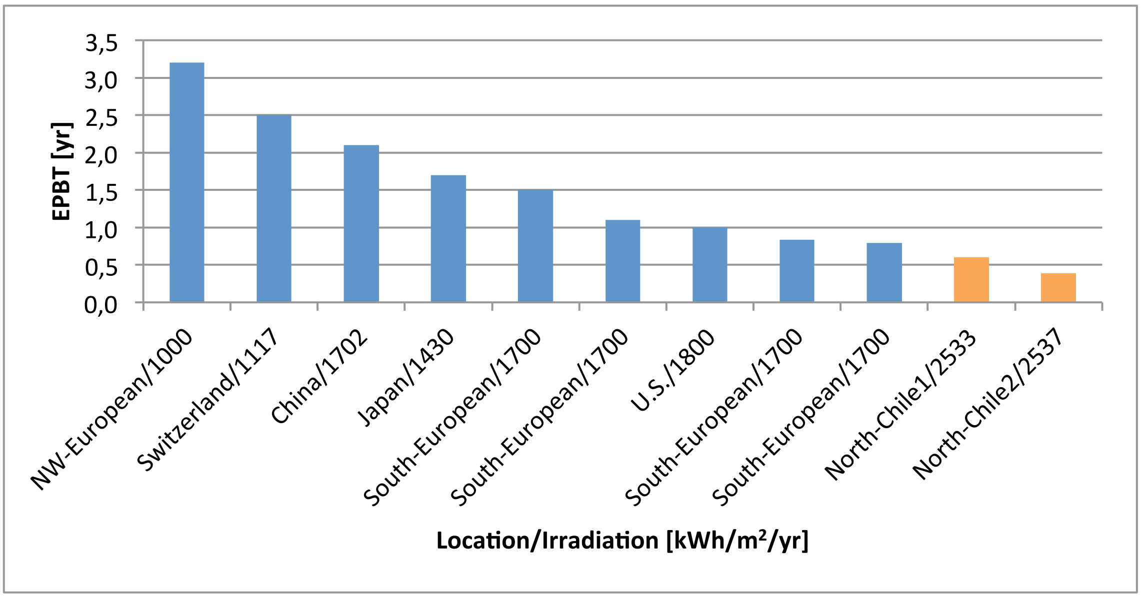


Figure 12 Energy Payback Time [yr] for CdTe PV at different locations and irradiations. Sources: Peng et al., 2013; this study.

2.2.2.- GREENHOUSE GAS (GHG) EMISSIONS

Currently, it is well accepted that the amount of grams of CO_2-equivalent emissions is a good metric for evaluating the comparative pollutants associated with a method of generating electricity.

Figure 13 shows a range of GHG emissions for different PV technologies, standardizing the irradiation at 1700 $kWh/m^2/yr$.[23] As it can be seen, CdTe stands as one with the lower range of GHG emissions between the studied technologies.

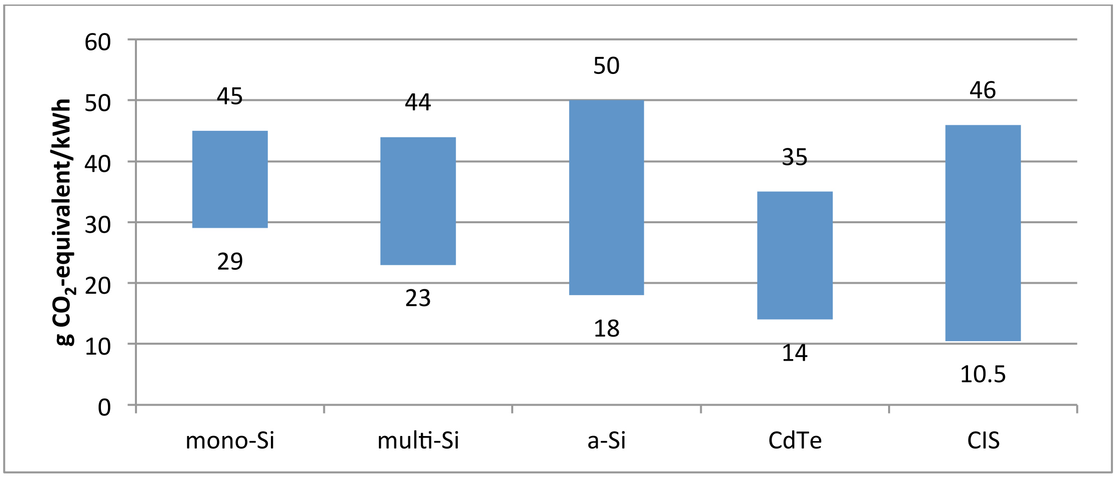


Figure 13 GHG emissions for different PV technologies. Irradiation standardized at 1700 [kWh/m2/yr]. Adapted from Peng et al., 2013.

[23]Peng, J., Lu, L., & Yang, H. 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255-274

For the calculation of the current GHG emissions (or GWP), the following formula was used:

$$CdTe\ Cradle\ to\ Recycling\ GWP = \frac{CdTe\ PV\ system\ GWP + Transportation\ GWP}{I \cdot \eta_{PV} \cdot PR \cdot L_t \cdot \left(1 - \frac{D_r}{2}\right)}$$

Where the variables are defined as:

I	Irradiation [kWh/m^2/yr]
η_{PV}	Panel efficiency [%]
PR	Performance Ratio [%]
L_t	Lifetime [yr]
D_r	Degradation rate [%/yr]

GHG emissions were calculated for the deployment of First Solar's modules under the conditions of northern Chile. Table 5shows the data and its sources used for the calculation.

	GWP [kg CO_2-eq/m2]	Source
CdTe PV system GWP	86.1	Held and Ilg (2011).
Solar Panel Delivery (Penang, Malaysia to Antofogasta Terminal, Chile)	3.82	Ecoinvent background process
End-of-life recycling (Antofogasta Terminal, Chile to Hamburg Terminal, Germany)	2.61	Ecoinvent background process
Solar Panel Delivery or EOL recycling (Antofogasta Terminal, Chile to Detroit Terminal, USA	2.14	Ecoinvent background process
Solar Panel Deliver or EOL recycling (Antofagasta terminal, Chile to Crucero, Chile)	0.74	Ecoinvent background process
Solar Panel Deliver or EOL recycling (Antofagasta terminal, Chile to Carrera, Chile)	2.16	Ecoinvent background process

Table 5 GHG emissions [g CO2-eq./kWh] for CdTe PV system and transportation

Using the information from Table 1 to Table 5, the GHG emissions for the different studied scenarios were obtained, which are shown in Table 6. For all the considered scenarios, the obtained global warming potential of CdTe PV power is approximately 12 g CO2 eq/kWh.

	Crucero (SING/Panel from MY/EOL GE)	Crucero (SING/Panel from US/EOL US)	Carrera (SIC/Panel from MY/EOL GE)	Carrera (SIC/Panel from US/EOL US)
Cradle to Recycling GWP [kg CO_2eq/m^2]	94.00	91.85	95.56	94.70
Irradiation [kWh/m^2/yr]	2841	2841	2837	2837
Total power output [kWh]	7795	7795	7782	7782
GWP [g CO_2eq/kWh]	**12.1**	**12.3**	**11.8**	**12.2**

Table 6 GHG emissions [g CO2-eq./kWh] for the 4 modeled scenarios

Figure 14 shows these results in comparison with previous published studies with different PV technologies and irradiations[24].

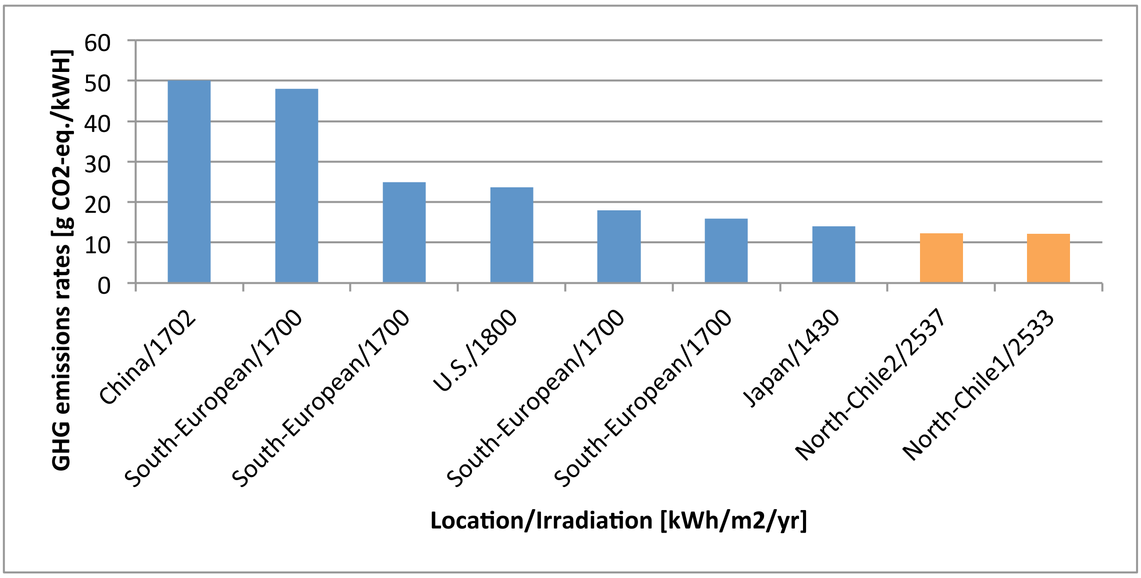


Figure 14 GHG emissions [g CO2-eq./kWh] for different PV technologies and irradiations[25].

It can be seen again that the current First Solar CdTe PV system under study obtained the lowest GHG emissions at both locations, owing to the high solar irradiation at the installation site.

Figure 15 shows the GHG emissions for different electricity sources, highlighting the current system under study as one with the lowest emissions rates, being 97% and 99% lower than SIC

[24] See Appendix 3.2 for more details
[25] Peng, J., Lu, L., & Yang, H. 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255-274

and SING Chilean electricity grids for each location.[26]

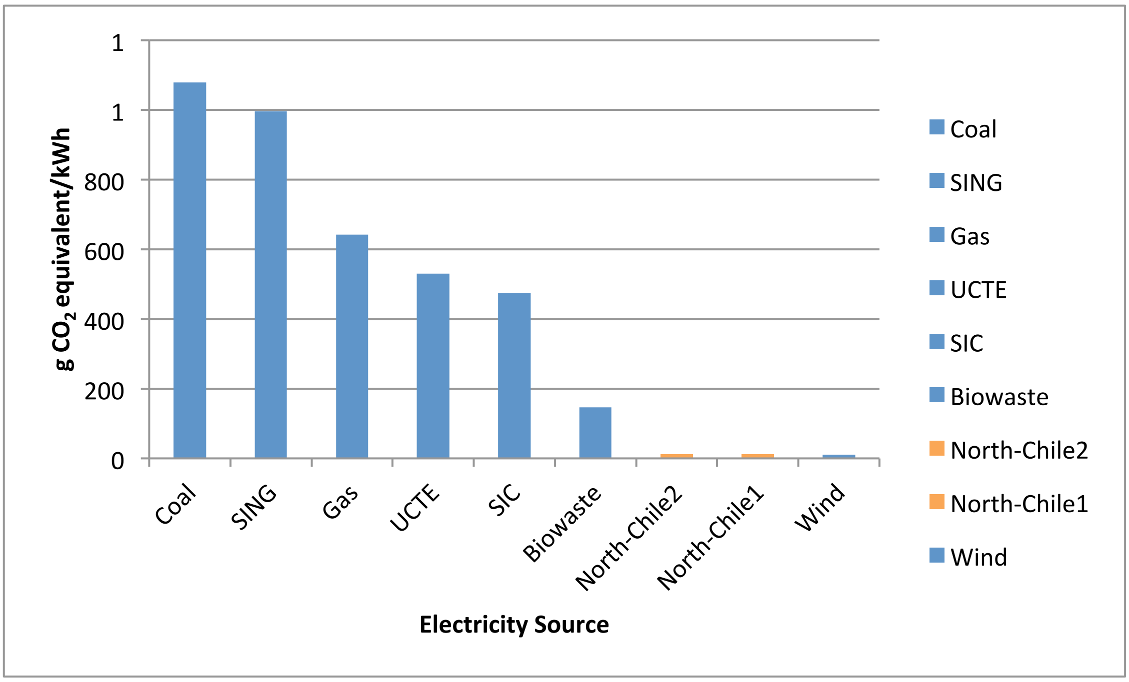


Figure 15 GHG emissions [g CO2-eq./kWh] for different electricity sources.

2.2.3.- LIFE CYCLE CADMIUM EMISSIONS

Cadmium is a highly toxic metal and due to the fact that CdTe PV modules contain cadmium compounds, there are concerns regarding the role that the widespread adoption of this technology could play in increasing cadmium pollution. This section reviews the emissions of cadmium to the environment throughout the life cycle of CdTe modules, and puts it in the context of other electricity generation technologies.

Fthenakis[27] studied in detail the atmospheric Cd emissions related to mining and processing of Zn ores (from where Cd is obtained), Cd purification, production of CdTe compound, and manufacturing, operation and end-of-life of CdTe PV modules. He found the total atmospheric emissions ranged from 19 mg Cd/GWh (reference case) to 67 mg Cd/GWh (worst case scenario), considering the average US radiation of 1800 kWh/m^2/year. As will be discussed in Section 2.3, the risk of Cd pollution during CdTe module operation is low, since it is stable under foreseeable operation conditions or accidents. Therefore, it is considered that there are no Cd emissions during the operation phase.

[26] Emissions rates obtained from Ecoinvent processes. More details in Appendix 3.3.-
[27] Fthenakis V.M., "Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production," Renewable and Sustainable Energy Reviews, 8, 303-334, 2004.

Raugei and Fthenakis[28] estimated total atmospheric emissions of CdTe PV module manufacturing (including upstream emissions) to be 1.3 mg Cd/m^2 of module, noting that the largest part of these emissions are related to components which are common to different PV technologies, including tempered glass, laminate material and transparent conductive oxide.

Atmospheric Cd emissions from First Solar's recycling process for CdTe modules, including semiconductor refining done by their suppliers, have been calculated by Sinha et al.[29] to be less than 0.006 mg Cd/m^2 of module.

These data were used to calculate the potential atmospheric Cd emissions during the life cycle of CdTe PV modules under the estimated total power output of 7788.5 kWh/m^2, considering a lifetime of 30 years and the average solar irradiation between the Crucero and Carrera sites. For the mining, smelting and refining Zn ore, we considered the economic allocation factor of 0.58% for Cd used by Fthenakis (allocation of emissions to co-production of Zn, Cd, Ge and In).

Life cycle activity	Air emissions (mg Cd/m^{2}modiule)	Air emissions (mg Cd/GWh)	Source
Mining of Zn ores	0.0001	0.01	Fthenakis, 2004
Zn smelting/refining	0.0016	0.21	Fthenakis, 2004
Cd purification	0.042	5.39	Fthenakis, 2004
CdTe production	0.042	5.39	Fthenakis, 2004
CdTe PV manufacturing	0.021	2.70	Fthenakis, 2004
Other module components	1.19	153	Raugei & Fthenakis, 2010
Balance of system	0.4	51	Raugei & Fthenakis, 2010
CdTe PV operation	0	0.00	Fthenakis, 2004
Recycling	0.0059	0.76	Sinha et al., 2012
Total	**1.71**	**219**	-

Table 7 Life cycle atmospheric Cd emissions from CdTe PV modules, considering Northern Chile solar irradiation

Table 7 shows the results for these calculations, with a total of 219 mg Cd/GWh produced under Northern Chile solar irradiation conditions.

When compared to other sources of electricity generation, the life cycle atmospheric Cd

[28] Raugei, M., and V. Fthenakis., Cadmium flows and emissions from CdTePV: future expectations, Energy Policy, 38 (9), 5223-5228 (2010).

[29] Sinha, P., M. Cossette, and J.-F. Ménard. 2012. End-of-life CdTe PV Recycling with Semiconductor Refining. Proceedings : 27th EU PVSEC, Frankfurt, Germany, pp. 4653 – 4656.

emissions from CdTe PV have been estimated by Fthenakis et al.[30] to be lower than alternatives such as other PV technologies, coal, oil and nuclear, and higher than natural gas or hydroelectricity, as shown in Figure 15. Specifically, when compared to coal power plants with particulate control devices, the authors found the emissions from ground-mounted CdTe PV to be 90 to 300 times lower.

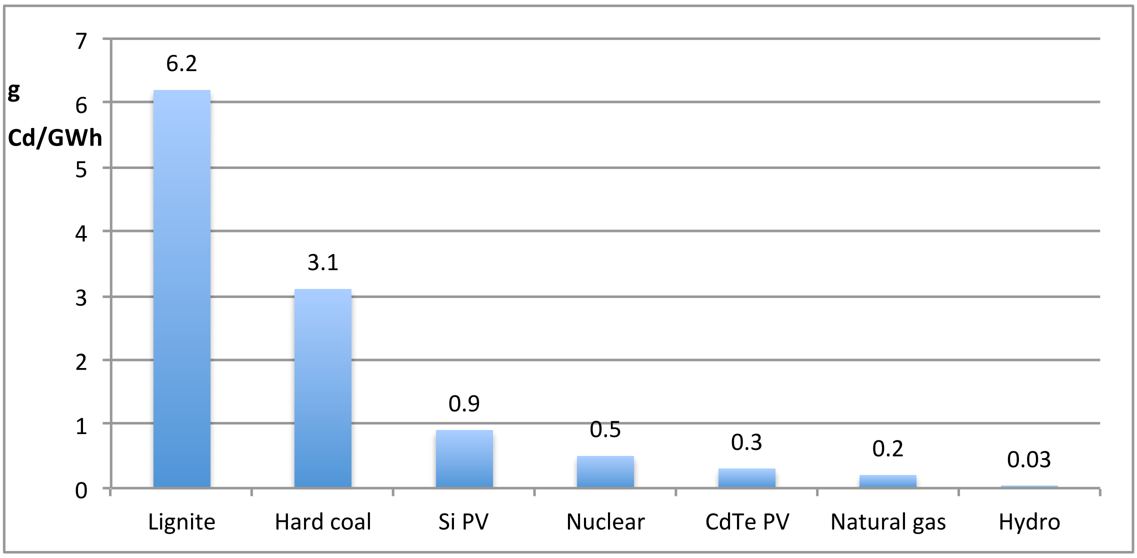


Figure 16 Life cycle atmospheric Cd emissions for different electricity generation options, Southern European conditions. Source: Fthenakis et al., 2008

The reason why Cd emissions from CdTe PV are lower than from other PV technologies, such as crystalline silicon PV, is the lower energy use required for manufacturing of CdTe modules. This also translates to lower life cycle emissions of other pollutants, including arsenic, chromium, lead, mercury, nickel, SOx, NOx, particulate matter, and greenhouse gases.[31]

Use of Cd in NiCd batteries and coal-based electricity generation both are higher Cd emitters than CdTe PV modules.[32]Cd emissions from the life cycle of CdTe in the future (2025 and 2050) are expected to be orders of magnitude lower than current emissions in Europe. The displacement of fossil fuel-based electricity and the sequestration of Cd in a stable form would have positive impacts on the environment.[33]

[30]Fthenakis, V.M., Kim H.C., and Alsema, E. 2008.“Emissions from Photovoltaic Life Cycles,” Environmental Science and Technology, 42, 6 (2008).
[31]Fthenakis, V.M., Kim H.C., and Alsema, E. 2008.“Emissions from Photovoltaic Life Cycles,” Environmental Science and Technology, 42, 6 (2008).
[32]Fthenakis V.M., “Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production,” Renewable and Sustainable Energy Reviews, 8, 303-334, 2004.
[33]Raugei, M., and V. Fthenakis., Cadmium flows and emissions from CdTePV: future expectations, Energy Policy, 38 (9), 5223-5228 (2010).

2.2.4.- TELLURIUM AVAILABILITY

With the increasing adoption of CdTe for large-scale PV power plants, the scarcity of Tellurium (Te) as a limiting factor for this technology's growth has been evaluated. Currently, Te is obtained as a by-product of copper refining.

According to Zweibel[34], the amount of Te required for CdTe PV module manufacturing is 91 tons/GW. It is expected that due to an increased demand for Te by the CdTe industry, Te prices would increase, which in turn should lead to more Te recovery from copper refining, and possibly to begin Te recovery from the refining of other metals, such as gold, zinc and lead. There are also a few identified sources of Te as a primary ore. Currently, increases in global Te production are coupled to increased copper production, which ranges from 1% to 3% per year. In addition to increasing Te supply, the demand per unit of electricity generated may be reduced by ongoing advances in CdTe PV module technology, such as reducing layer thickness and increasing module efficiency. Taking into account these considerations, Zweibel concludes that projections of CdTe PV potential based on a nearly static Te availability for the next 20 years result in significant underestimations.

Marwede and Reller[35] studied the potential effect of recycling of CdTe PV modules on the availability of Te for the CdTe PV industry, through material flow analysis. They generated three different scenarios ("breakthrough", "steady advance" and "slow progress"), considering different assumptions in material utilization, lifetime of the modules and recycling rates (both end-of-life and from manufacturing processes). They concluded that by 2038 Te demand for CdTe PV modules could be met entirely by end-of-life recycled module material if substantial material efficiency and effective collection and recycling streams are achieved ("breakthrough" scenario).

Considering these scenarios, demand for Te feedstock from primary sources would peak between 2021 and 2024 and, under plausible conditions, shouldn't face supply shortages. Recycling of CdTe modules is essential to conserve scarce Te, and additionally, to ensure the avoidance of Cd emissions to the environment. This will be driven both by economic feasibility of used module collection and recycling, and by regulatory measures, such as producer responsibility programs.

Fthenakis[36] projected scenarios of increases in Te availability, improvements in cell efficiency and decreased semiconductor layer thickness, and recovery of Te at the end-of-life of PV modules. He concluded that Te availability could support an annual production of 16-24 GW_p in 2020, 44-106 GW_p in 2050 and 60-161 GW_p in 2075.

[34] Zweibel, K. 2010. The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics. Science, Vol. 328: 699-701.
[35] Marwede, M. and A. Reller. 2012. Future recycling flows of tellurium from cadmium telluride photovoltaic waste. Resources, Conservation and Recycling 69: 35– 49.
[36] Fthenakis V.M. 2012. Sustainability metrics for extending thin-film photovoltaics to terawatt levels. MRS Bulletin. Vol. 37: 425-430.

Figure 16 summarizes the management strategies in different parts of the product's life cycle that can help ensure that CdTe PV growth is not limited by Te availability.

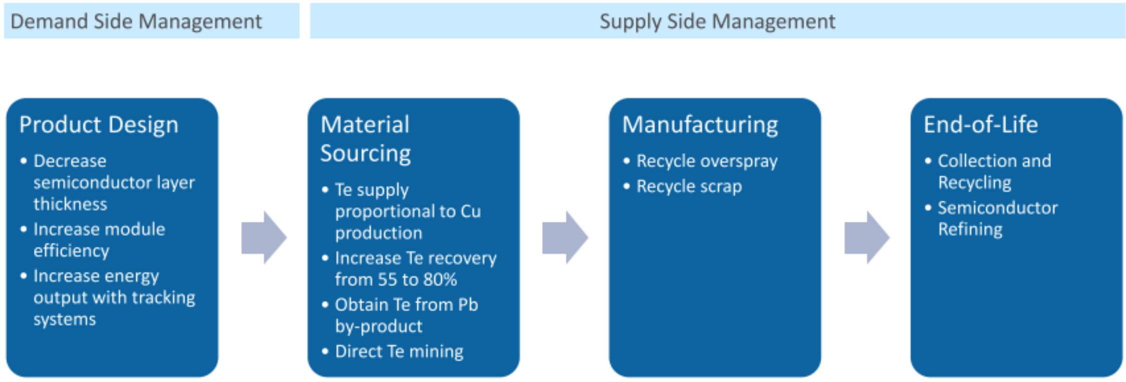


Figure 17 Life cycle management strategies for tellurium availability.[37]

2.2.5.- WATER USE

In addition to greenhouse gas and other pollutant emissions, the demand of freshwater for electricity generation is an important sustainability indicator to assess different technologies.

A distinction needs to be made between two metrics regarding water use: water withdrawal and water consumption. The first refers to water that is taken from nature (such as lakes, rivers, aquifers and streams). The latter refers to water that is "used up" in a process (i.e. evaporated, transpired or incorporated into products) and thus removed from the immediate water environment. Seawater is often excluded from these metrics, since it is considered to be unlimited for practical purposes. The difference between water withdrawal and water consumption is known as water discharge.[38] In general, there is a scarcity of information regarding water consumption, so we focus our discussion on water withdrawal.

Fthenakis and Kim[39] investigated freshwater use for different conventional and renewable electricity generation technologies for a US context, based on previous published studies and using a life cycle approach. They quantify water withdrawal for CdTe module manufacturing to be 787.3 L/MWh, from which 575 L are related to upstream processes (raw materials for the modules), 0.8 L/MWh from the module manufacturing site and 211.5 from the balance of system

[37] Sinha, P. 2013. Life cycle materials and water management for CdTe photovoltaics. Solar Energy Materials & Solar Cells, 119, 271-275.
[38] Inhaber, H. 2004. Water Use in Renewable and Conventional Electricity Production. Energy Sources, 26(3), 309–322; Sinha, P., A. Meader, and M. de Wild-Scholten. 2013. Life Cycle Water Usage in CdTe Photovoltaics, IEEE Journal of Photovoltaics, Vol. 3, Number 1, pp. 429-432.
[39] Fthenakis, V., and H. C. Kim. Life-cycle uses of water in U.S. electricity generation. Renewable and Sustainable Energy Reviews vol. 14, pp. 2039–2048, 2010.

(based on an irradiation of 1800 kWh/m^2/year, a lifetime of 30 years and a performance ratio of 0.8). Water use during CdTe PV plant operation is considered to be zero, since they can be cleaned without water or not cleaned at all, depending on soiling and rainfall conditions of the site. In fact, First Solar recommends no wet cleaning for most conditions, and have developed a special brush for the dry cleaning of modules when needed.

As shown in Figure 17 (in a logarithmic scale), the water withdrawal for CdTe PV is lower than for Si PV, coal, oil/gas, nuclear and biomass electricity generation. Amongst the compared options, only wind power and hydroelectricity have a lower water demand (water withdrawal by hydroelectric power plants was assumed by the authors to be zero although there is water consumption from evaporation). The authors concluded that moving to technologies such as PV and wind power offer the best option for reducing water demand by the electricity sector.

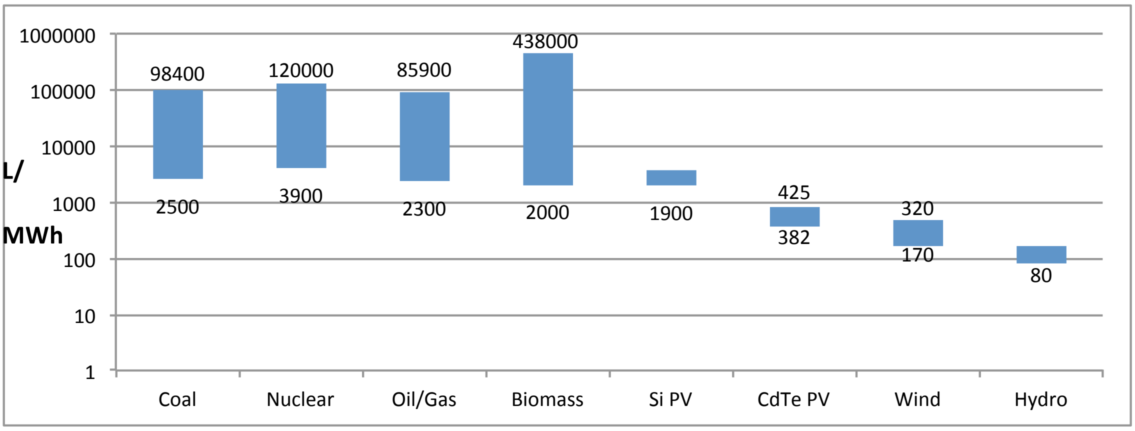


Figure 18 Life cycle water withdrawal for different energy generation options (Sources: Fthenakis and Kim, 2010; Sinha et al., 2013)

Water withdrawal for the life cycle of CdTe PV modules, considering First Solar's manufacturing facilities, have recently been published[40]. Total withdrawal ranges from 382 to 425 L/MWh (the variability owing to two different scenarios for the lifetime of the BOS, 60 and 30 years respectively). Approximately 12% of this is from direct water use (including water use for module manufacturing and for site preparation and dust suppression during construction), and the rest is embedded in upstream processes and purchased electricity (approximately 48% from module manufacturing, 28% from BOS manufacturing and 12% from module collection and recycling). The displacement of current electricity generation (considering the current Southwest US electricity grid) from CdTe PV operation would avoid between 1700 and 5600 L/MWh.

[40]Sinha, P., A. Meader, and M. de Wild-Scholten. 2013. Life Cycle Water Usage in CdTe Photovoltaics, IEEE Journal of Photovoltaics, Vol. 3, Number 1, pp. 429-432.

2.2.6.- LAND USE AND BIODIVERSITY

The potential widespread deployment of PV solar parks has raised concerns related to the amount of land required and its possible effects on biodiversity. This is an issue that is still not well understood, and where more research is needed. This section reviews some relevant publications on the subject.

Turney and Fthenakis[41] reviewed the available literature on environmental impacts from the installation and operation of large-scale solar power plants. They included aspects related to land use intensity, wildlife, human health and well-being, geohydrological resources and climate change, considering a total of 32 impacts. When compared to traditional electricity generation in the US, solar is found to be beneficial for 22 of the 32 considered impacts. From the other 10 impacts, 4 are considered neutral and 6 in need of further research, while no impacts were considered negative relative to the current electricity sources which solar energy could potentially displace. It is pointed out that the impacts per kWh produced are lowest in areas with high solar irradiation, such as deserts, because of the higher electricity output per surface used. In what follows, we discuss the impacts related to land use and wildlife.

From a life cycle perspective, solar power plants occupy less land than coal (including surface mining) per unit of electricity produced for operating periods beyond 25 years. This is owing to the fact that the amount of land occupied for solar power is not increased once the plant is in operation, whereas for coal, there is a constant need for mining to obtain the fuel, which results in increased land occupied. In the case of solar power, depending on the previous use of land, disturbance can be quite limited, whereas for coal mining the disturbance will be very significant. For a 30-year old PV power plant, Turney and Fthenakis estimated that the life cycle land occupation would be 15% lower than for a coal power plant. Because land use is static during the operation of a PV power plant, it is easier to return the land to its natural state after the decommissioning phase.

Regarding impacts to wildlife from solar power plants, these include the enclosing of the area and thus limiting movement by animals, soil and vegetation disturbance, and changes in microclimates. These potential impacts have not been studied in depth, and are expected to be tightly correlated to the biodiversity of the power plant site. It is mentioned that true deserts (such as the Atacama desert) are the least biodiverse of the considered biomes. Nevertheless, endangered species can be found in any biome, so a customized ecosystem study for the surroundings of each power plant site is recommended.

Impacts from global warming are expected to have serious effects on biodiversity, because of increased temperatures, droughts, fires and parasitic diseases[42]. As it has been described in the

[41] Turney, D. and V. Fthenakis. 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews, 15: 3261–3270.
[42] Fthenakis, V., Blunden, J., Green, T., Krueger, L., &Turney, D. 2011. Large photovoltaic power plants: Wildlife impacts

Section 2.2.2, PV (particularly CdTe) offers an energy source with significantly lower life cycle greenhouse gas emissions than the available alternatives, as well as lower emissions of pollutants that affect wildlife as well as humans.

Fthenakis et al.[43] describe how First Solar, as well as one of its competitors, have implemented best practices to prevent and mitigate impacts to wildlife from solar power plants in California. These include:

- Avoidance or minimization of conflicts: conduct surveys of habitats and species, design layouts to avoid sensitive areas, employing low-impact site preparation and construction techniques, employ stewardship measures such as fencing with openings for small animals to be able to circulate and the avoidance of toxic chemicals.
- Restoration: restoring and maintaining vegetation cover removed during construction to enhance habitat.
- Developing compensation areas for the preservation of species when building projects in environmentally sensitive areas, if necessary.

The authors mention there are possible beneficial impacts from PV power plant installation, such as site protection from other activities and funding for biodiversity management and monitoring.

A report published by the Renewable Energies Agency of Germany[44] concluded that depending on site selection and practices employed, solar parks may be of limited negative impact or even beneficial impact to biodiversity. They list the key points of the criteria used by the German Society for Nature Conservation (NABU) for the construction of environmentally sound solar parks:

- “No intervention in protected areas (preference to be given to sites previously subjected to high stress levels, e.g. intensively farmed or brownfield sites).
- Compatibility assessment based on the European Birds Directive.
- Avoiding exposed sites (solar plants should not dominate the landscape).
- Sealed area of site should be small (< 5%), where sealing refers to sealing of soil (e.g., with concrete footings).
- Fencing should not present a barrier to small mammals and amphibians.
- Sites to be maintained with the help of sheep grazing or mowing, no synthetic fertilizers or pesticides.
- Local community to be involved in the project planning to increase acceptance.”

It is important to mention that these criteria are focused in the German context and not

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and benefits. 37th IEEE Photovoltaic Specialists Conference, Seattle, WA,

[43] Fthenakis, V., Blunden, J., T. Green, L. Krueger, and D. Turney. 2011. Large Photovoltaic Power Plants: Wildlife Impacts and Benefits. IEEE Photovoltaic Specialists Conference, Seattle, WA.

[44] Peschel, T. 2010. Solar parks – Opportunities for Biodiversity: A report on biodiversity in and around ground-mounted photovoltaic plants. Renews Special, Issue 45.

necessarily all of them will be directly applicable to Northern Chile (for example, solar plants in exposed sites in a desert landscape would not necessarily be a problem).

Although there is no international standard for responsible PV land use, best practice recommendations for nature conservation, with relevant examples, are described in the report for the planning, construction and operation of solar power plants:

- Planning stage: careful site selection, taking local conditions into account in the environmental impact assessment.
- Construction stage: environmental construction planning and monitoring, avoiding soil sealing, minimizing the canopy and reflection effects, helping conserve the regional genetic diversity of plants, avoiding barrier effects caused by fencing.
- Operation stage: long-term monitoring, environmental site conservation and maintenance.

The report identified the installation of solar power plants in previously cleared agricultural land with poor species diversity as the main opportunity regarding biodiversity enhancement.

2.2.7.- EXTERNAL COSTS

As it has been discussed in the previous sections of this review, photovoltaic electricity generation, and particularly CdTe PV, provides significant environmental benefits compared to traditional sources of electricity generation, such as fossil fuels. One way to incorporate this dimension into the comparison of different electricity sources is by calculating the "external costs" related to environmental and health damages in monetary terms. The ExternE projects (and the NEEDS project that followed), from the European Union, provide a methodological basis for these calculations. This approach for environmental assessment is well accepted, even though there is high uncertainty and room for debate regarding the monetary valuation of environmental impacts[45].

This external cost, added to the levelized cost of electricity (LCOE), can be used to determine the total cost of electricity. Even though currently the total cost of electricity will not be reflected in the marketplace, it is a relevant metric for the decision-making processes, allowing for the consideration of societal benefits of cleaner sources of energy.

Sinha et al.[46] recently studied the total electricity cost of CdTe PV in comparison with conventional natural gas and coal electricity generation. Their calculations considered private cost (LCOE) plus the addition of a life cycle environmental cost (considering GHG, SO_2. NO_x, Hg, Pb, Cd, NMVOC, $PM_{2.5}$ emissions and water use) and a performance cost (related to

[45] Fthenakis, V., and E. Alsema. 2006. Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status. Prog. Photovolt: Res. Appl. 14:275–280.
[46] Sinha, P. M. de Wild-Scholten, A. Wade, and C. Breyer. 2013. Total Cost Electricity Pricing of Photovoltaics. EU PVSEC, Paris, France, 6DO.10.4.

variable sources of energy such as wind and solar). The results showed CdTe PV to be competitive with fossil fuels, with a total cost of energy range (in USD $2011) of $0.07-0.15/kWh, while natural gas total cost has a range of $0.07-0.21/kWh and coal $0.10-0.26/kWh. Environmental cost of CdTe PV was quantified to be less than $1/MWh, while natural gas had a mid-range environmental cost of $26/MWh (mainly attributable to GHG and SO_2emissions) and coal had a mid-range cost of $50/MWh (mainly attributable to GHG and SO_2 emissions and water use).

2.3.- SAFETY DURING CdTe PV MODULES OPERATION

First Solar provides a warranty against defects in materials and workmanship under normal use and service conditions for 10 years following delivery to the owners of the solar modules. They also warrant that the solar modules will produce at least 90% of the labeled power output rating during the first 10 years following their installation and at least 80% during the following 15 years. Moreover, to ensure operation and safety of the CdTe modules, First Solar is certified by different standards, which will be described in this section.

Apart from this, an analysis and evaluation of the potential risks along the modules working life will be performed. The working life is understood as the module life from the time the product is finished and ready to be shipped to the customers, until the module is decommissioned and sent to be recycled. Along this time, at least, the following operations will occur:

- Modules transportation to customer's site.
- Modules installation on final localization.
- Operational period.
- Modules decommissioning and/or collection.
- Modules transportation to the recycling plant.

As has been described before, the potential risk associated with CdTe technology is due to the possibility of Cd releases during the working life causing some potential risks to people and the environment. The potential risk-related situations that may happen to the modules at any time are: breakage, fire, and slow degradation (leaching) and potential release of CdTe. These four possibilities will be also reviewed in the following sections.

2.3.1.- SAFETY AND RELIABILITY CERTIFICATIONS

Modules from First Solar are certified according to the following standards:

- IEC 61646 Thin film terrestrial PV modules – Design qualification and type approval, which includes a specific test sequence for thin film modules with a special light soaking step. This International Standard lays down requirements for long-term operation in general open-air climates as defined in IEC 60721-2-1.The object of this test sequence is to determine the electrical and thermal characteristics of the module and to show, as far as possible within reasonable constraints of cost and time, that the module is capable of withstanding prolonged exposure in general open-air climates.
- IEC 61730 PV module safety qualification, application class A. This standard describes the fundamental construction and testing requirements for photovoltaic (PV) modules in order to provide safe electrical and mechanical operation during their expected lifetime.

Specific topics are provided to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses.

- IEC 61701 Salt mist corrosion of PV modules. This test has as object to determine the resistance of the PV module to the corrosion due to salt mist. In this Standard, the evaluation of the compatibility of the materials, quality and uniformity of their coatings is performed.
- IEC 60068-2-68 Environmental testing. Tests. Dust and sand. This Standard specifies tests methods to determine the effects of dust and sand suspended in air on the PV modules.
- UL 1703Flat-Plate Photovoltaic Modules and Panels. This Standard also ensures safety during installation and operation. The certification of First Solar allows the modules to be used in PV systems up to 1,000V.
- First Solar Series 3 Black is also the first thin-film PV module to pass the extended accelerated life cycle testing protocols of the Thresher Test and Long Term Sequential Test[47].

2.3.2.- BREAKAGE

A module can suffer a breakage at any stage of its working life. Transportation, installation, maintenance operations, and decommissioning involve handling. In these operations there is a chance to damage and/or break the glass covers or any other part of the module. This type of damage may also happen during the operational period. However, module breakage rates are very low and are estimated based on First Solar experience at 0.03 %/yr from its installation through its operation of up to 25 years[48].

In case of module breakage, the potential risk occurs because CdTe can be exposed to the environment and people. In that situation, CdTe remains stable in a broken module as a solid compound and no chemical degradation occurs. Additionally, First Solar modules are constructed by laminating the CdTe layer between two sheets of glass with an industrial polymeric adhesive. When modules crack, it is rare for the breakage to result in delamination of the module, which reduces potential for CdTe to be exposed to the environment. The low vapor pressure of the compound at normal operation conditions ensures no emissions of Cd and Te to the environment.

[47] Sinha, P..” Life cycle materials and water management for CdTe photovoltaics”. Solar Energy Materials & Solar Cells, 119, 271-275. 2013
[48] “Appendix 10: PV module detection and handling plan”, Topaz solar farm project. First Solar, 2012

Figure 19 Example of typical breakage pattern of First Solar modules

If severe breakage happens during handling, CdTe can come in contact with people's skin and clothes; however, CdTe hazard is primarily via inhalation exposure. In the bibliography review, no evidences have been found for CdTe absorption through the skin and no acute effects have been reported to eyes or skin[49]. In case of contact with CdTe powder, it is recommended to flush with water and remove any contaminated clothing because dust may provoke skin irritation.

During the PV system's routine maintenance, modules are monitored for breakages through visual inspection and power output monitoring (when available)[50]. In conclusion, in our opinion, a damaged or broken module from First Solar CdTe technology can be classified as zero risk at any step of its life cycle.

A special comment on earthquakes is included as they are not uncommon for the region, particularly in Chile. Even though no specific information or field data about the issue was available at the time of this review, broken module detection and handling protocols[51] have been used to address earthquake risks in the permitting of large-scale PV projects in the western U.S. If an earthquake were to happen, and assuming that the seismic activity was strong enough to damage the structures holding the PV modules or the modules themselves, we can say, based on the related studies and information (mentioned in this section), that we maintain the conclusion that a broken module from First Solar CdTe technology can be classified as zero risk. Nevertheless, we recommend investigating the seismic performance of the structures and modules, to inform their design and reduce their risk of breakage during the likely event of an earthquake during their lifetime in Chile or other highly seismic areas.

2.3.3.- HAZARDOUS CIRCUMSTANCES (FIRE)

Fire risk is a controversial aspect for CdTe photovoltaic applications. The hazardousness is

[49] 5N PLUS, Material Safety Data Sheet V2, 2007
[50] P. Sinha, R. Balas, L. Krueger, A. Wade, "Fate and transport evaluation of potential leaching risks form cadmium telluride photovoltaics", Environmental Toxicology and Chemistry, 31, 7, 2012, 1670-1675
[51] "Appendix 10: PV module detection and handling plan", Topaz solar farm project. First Solar, 2012

related to Cd emissions as fumes or particles from CdTe decomposition at high temperatures. The first available scientific publication in that respect has been performed by Fthenakis and coworkers[52].

The experiment carried out by Fthenakis[52] was set up to follow the standard temperature rate curve described in the ASTM Standard E119-98 for Fire Test Building Construction and Materials and UL protocols. Special care was taken to avoid any Cd and Te losses during the experiment and a very precise description of the methodology to collect and analyze Cd and Te content was included. Equipment descriptions, including uncertainty values, and error bars in data points were also provided. They concluded that:

- Only 0.5% ± 0.1% of Cd was emitted during the test in the temperature range from 760 ºC to 1100 ºC.
- The pathway for Cd losses was the perimeter of the sample before the two sheets of glass fused together.
- Most of Cd diffuses into the glass matrix.
- The emission is very low at temperatures between 700 ºC and 900 ºC but it was larger at 1000 ºC to 1100 ºC.

In a fire, the EVA (laminate) layer burns or decomposes at approximately 450 ºC and glass softening occurs at 715 ºC. The experiment showed that 99.5% of the cadmium content in a CdTe module diffuses into the glass during the fire and is encapsulated into the two molten glass matrices; a small amount of cadmium escaped from the module perimeter before the two glass slices fused together.

The experiment was performed using EVA as laminate material. Nowadays, First Solar CdTe modules use a different (laminate) material. After the analysis of the technical information supplied by First Solar regarding the thermal behavior of the new material, in our opinion this change does not affect the conclusions extracted from the experiment.

The experiment was performed with 25 cm x3 cm samples without any CdTe edge exclusion, which is not the actual First Solar CdTe modules configuration. In that situation, Cd emissions are less than 0.04% of the total Cd content. Furthermore, they estimated the Cd emissions to be 0.06 mg/GWh, assuming the probability of a residential fire in wood-frame houses in the US to be 1 over 10^4, 7 g Cd/m^2 content, 10% electric conversion efficiency and 1800 kWh/(m^2·yr) of total irradiation. In the less probable case that the module breaks in small pieces during the fire, Cd emission would rise to 0.8 mg/GWh. This scenario is the worst case.

Fthenakis considered Cd emissions to be zero in ground mounted installations due to the lack of combustible materials in that configuration.

[52] V. Fthenakis, M. Fuhrmann, J. Heiser, A. Lanzirotti, J. Fitts and W Wang, “Emission and encapsulation of cadmium in CdTe PV modules during fires” Progress in Photovoltaics: Research and Applications, 13, 8, 713-723, 2005

In 2011, the Bavarian Environmental Protection Agency performed a calculation about emission of cadmium and oxide fumes (CdO and TeO_2) during fires of photovoltaic modules containing CdTe under certain conditions[53]. Under the most conservative conditions of the study, cadmium emissions are below AEGL-2/ERPG-2[54] levels so it is concluded that a serious danger for the immediate neighborhood when CdTe modules burn can be excluded.

Although, in our opinion, Fthenakis scientific research is outstanding, a different opinion was found[55]. Some experts disagreed on the way the experiment was set up pointing out that temperatures of 1200 ºC are not unheard of in building fires, that the modules are installed in a certain angle and that the temperature could be non-uniform. A possibility for the laminate material to melt that might produce a slicing of the cover glass was also arising, in that scenario CdTe is completely exposed to the environment and can completely decompose. Regarding this controversy, no data was presented by the experts to support their opinion; additionally, in our bibliography review, we did not find any scientific studies, data or information that reproduces those specific situations. Note that the concern regarding a potentially higher emission rate was considered in the Bavarian Environmental Protection Agency study[53] discussed above, which evaluated the worst-case emissions scenario of total release of Cd content from CdTe PV module fire.

To go one step forward, we calculate the actual Cd emissions produced by fires involving First Solar CdTe modules. Using the installed power of CdTe modules as of year 2010[55] and considering that all the modules installed suffer the same damage in the fire, the actual calculated Cd emission is 11.2 g, and assuming a worst case scenario (modules break in small pieces) the actual Cd emitted to the environment is 140 g. For the calculation, data like grams of Cd /m^2, probability of fire occurrence and Cd emissions have been taken from reference 52.

In the only fire event involving First Solar modules described in the literature[56], only 0.5 tons out of the 5 tons of modules installed were affected by the fire, so the actual calculation is very far off from the real described accident.

In our opinion, in the event of a fire accident, Cd emission is very low and the risk to humans and environment is negligible.

2.3.4.- SLOW DEGRADATION

A second concern for the environment and health related to CdTe PV applications refers to the

[53] "Calculation of emissions in case of fire in a photovoltaic system made of cadmium telluride modules", Bavarian Environmental Protection Agency, 2011

[54] AEGL: Acute Exposure Guideline Levels; ERPG: Emergency Response Planning Guidelines; Severity degree 2: Threshold to irreversible effects on other severe, long-lasting health effects or effects preventing flight from the scene

[55] First Solar data

[56] D. Sollmann, C. Podewils, "How dangerous is cadmium telluride?" Photon International 3, 100-109, 2009

possibility of cadmium releases produced by different leaching effects as dissolved Cd is considered a pollutant for water and soil. Leaching tests are designed to evaluate this potential risk.

In a leaching process, the media environmental conditions are critical; parameters like pH, complexation, redox potential, ionic strength, leaching time, sample surface and liquid/solid ratio may strongly affect the solubility of materials. In waste disposal landfills, these parameters are not controlled. Several leaching tests have been developed to simulate different conditions[57].

Specifically, during the working life of the PV module, the only possibility to release cadmium to water or soil is by an accident involving a broken or damaged CdTe module to be exposed to rainwater. Steinberger performed an outdoor experiment to simulate that situation[58]. In the experiment performed, different sample sizes (referenced as "10 mm pieces" and a complete module) were tested in order to include the worst case scenario. From his experimental results, it is concluded that CdTe area exposed to rainwater is a critical variable. The 10 mm fragments sample showed a Cd concentration value of 1 mg/L. The study considers that, in a realistic scenario, the ratio between broken module area and roof area would be only 1/200 so, multiplying the result of the experiment with this assumed value, the concentration in water collected from a roof would be 5 µg/L, which is in the limit of the German drinking water regulation. Also from that scientific study, results for soil contamination revealed a slight increase in Cd concentration respect to the natural abundance. However, in our opinion, the experiments are not well described in the study, and no clear conclusion can be extracted from them.

In 2012, another study about leaching was published by Sinha et al.[59] based on calculations of the potential impacts to soil, air and groundwater, a worst case rainwater leaching from CdTe broken modules in a commercial building scenario was modeled. The obtained Cd exposure results were one to five orders of magnitude below human health screening levels of California and southern Germany. In this context, the study demonstrates that potential health risk to on-site workers or off-site residents is unlikely.

Additionally, First Solar CdTe PV modules passed the Toxicity Characteristic Leaching Procedure (TCLP) test (according with U.S. EPA Method 1311) with <1.0 mg Cd/L in leachate so it is classified as non-hazardous waste in the U.S. In Europe, it is considered also as a non-hazardous waste because the Cd content in CdTe modules is below 0.1% by weight threshold[60]. As noted earlier, the glass-laminate-glass construction of a First Solar module greatly reduces the probability that a broken module will expose a significant portion of the

[57] A. Finke, A. Kriele, W. Thumm, D. Bieniek, A. Ketrup, "Leaching tests with thin film solar cells based on copper indium diselenide (CIS)" Chemosphere 32, 8, 1633-1641, 1996
[58] H. Steinberger, "Health, Safety and Environmental Risks from the Operation of CdTe and CIS Thin-film Modules", Progress in Photovoltaics: Research and Applications 6, 1998, 99-103
[59] P. Sinha, R. Balas, L. Krueger, A. Wade, "Fate and transport evaluation of potential leaching risks form cadmium telluride photovoltaics", Environmental Toxicology and Chemistry, 31, 7, 1670-1675, 2012,
[60] First Solar documentation, 2013

semiconductor to the environment in the event that a broken module remains in the field.

In Chile, a study[61] conducted by the National Center for the Environment (CENMA) on five samples from First Solar's modules, concluded that according to Chilean regulations:

- None of the analyzed samples show characteristics of acute toxicity hazards.
- These samples must be qualified as non-hazardous regarding chronic toxicity associated to the presence of carcinogenic substances.
- None of the analyzed samples show characteristics of chronic toxicity hazards associated to non-carcinogenic substances.

In normal operating conditions, and if breakage does not occur, CdTe is not exposed to the environment, so Cd leaching risk during operational life is zero. In order to avoid any risk in this regard, a proper maintenance operation to detect any damage in the modules is recommended.

Referring to the likely location of First Solar's plants in the north of Chile, rainfall is scarce and the region is among the driest in the world, which lessens even more the likeliness of any leaching occurring.

2.3.5.- END-OF-LIFE

Once CdTe PV modules have reached their end-of-life, they will likely be decommissioned and will either be recycled or be disposed as waste. In the European Union the Directive on Waste Electrical and Electronic Equipment has mandated collection and recycling of all decommissioned PV products beginning in February 2014 through inclusion of PV in the recast Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment. First Solar is currently the only PV company operating high-value recycling on a global and industrial scale.

With regard to end-of-life disposal of CdTe PV modules, the scientific study presented by Kaczmar[62] at the Society of Environmental Toxicology and Chemistry North America 33rd Annual Meeting in 2012 investigated the hazards associated with potential releases of leachate from disposal of CdTe PV modules from an unlined landfill under acidic and basic conditions. This work used the U.S. Delisting Risk Assessment Software (DRAS) to simulate the potential human health and environmental impacts associated with the generation and release of leachate from a 25 MW_{ac} project decommissioned during one calendar year. The software makes use of the waste volume and TCLP data (Toxicity Characteristic Leaching Procedure) to calculate through Monte Carlo simulation the carcinogenic risk and non-carcinogenic hazards

[61] CENMA, 2013. "Estudio de toxicidad aguda y crónica asociada a la concentración de metales en muestras denominadas 130821031117, 130806250325, 130804262920, 130803031839, 130823040982." Preparado por el Centro Nacional del Medio Ambiente de la Universidad de Chile para First Solar Energía Ltda.

[62] S. Kaczmar, "Evaluation of potential health and environmental impacts from end-of-life disposal CdTe photovoltaics" Society of Environmental Toxicology and Chemistry (SETAC) North America 33rd Annual Meeting, 2012

associated with the landfilled material (Cd from CdTe PV panels in this case). This DRAS model evaluates risk for several groundwater exposure scenarios (ingestion of groundwater, dermal absorption while bathing with groundwater, and inhalation of groundwater volatiles while showering) and for four surface exposure pathways (ingestion of surface water, ingestion of surface soil, ingestion of fish, and inhalation of vapor and particles). According to this study, the one-time disposal of CdTe modules from a 25 MW_{ac} project to an unlined landfill is not likely to represent significant cancer risks or non-cancer hazards, since aggregate cancer risk and non-cancer hazard incidence were well below the screening limits.

Apart from the aforementioned work, another study conducted by the Norwegian Geotechnical Institute (NGI) in 2010 has also investigated the environmental risks regarding the use and final disposal of CdTe PV modules[63]. According to this study, the leaching values exceeded the limits for disposal at a landfill for inert waste, but remained within the limits for ordinary and hazardous landfills (according to Norwegian waste regulation, Chapter 9, Annex II). Therefore, the risk of uncontrolled spreading of Cd and Te contamination in connection with the disposal of CdTe modules at approved landfills is considered to be low, taking into account that current landfills have strict requirements for bottom and side sealing and for the collection of landfill leachate. Nevertheless, uncontrolled dumping of CdTe modules will provide greater environmental risks compared with controlled disposal. Responsible end-of-life management is important for all PV technologies as use of environmentally sensitive materials (e.g. Pb, Cd, and Se compounds) is common in the industry.

In the particular case that module recycling takes place in the US — given that this was their origin — their shipping requires that the CdTe modules be qualified as a non-hazardous material. From the results from the study carried out by CENMA, described in the previous section, it is expected that the waste material from First Solar's PV modules will be qualified as non-hazardous by the Chilean environmental authority. Recycling in other countries, such as Germany or Malaysia, are not subject to this condition for their shipping.

[63] G. Okkenhaug, "Environmental risks regarding the use and final disposal of CdTe PV modules" Norwegian Geotechnical Institute, 2010

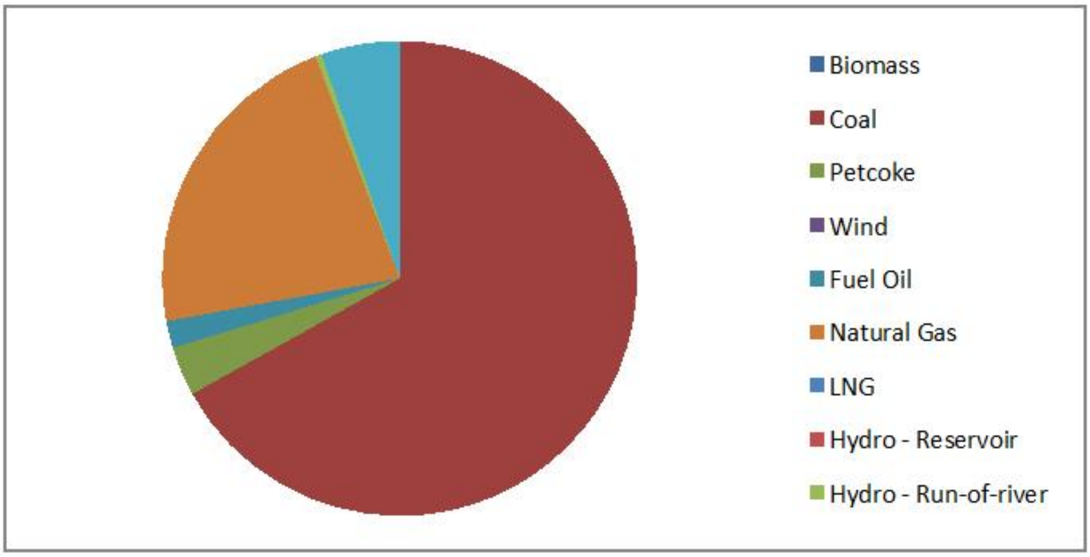
3.- APPENDICES

3.1.- CHILEAN SIC & SING ELECTRICITY GRID COMPOSITION

The electricity grids used on the present studies were an average from year 2010 to 2012, to include the interannual variability in rainfall, which affects directly the percentage of hydropower present at SIC electricity grid. Data was obtained from the National Commission of Energy (CNE)[64].

3.1.1.- SING ELECTRICITY GRID COMPOSITION

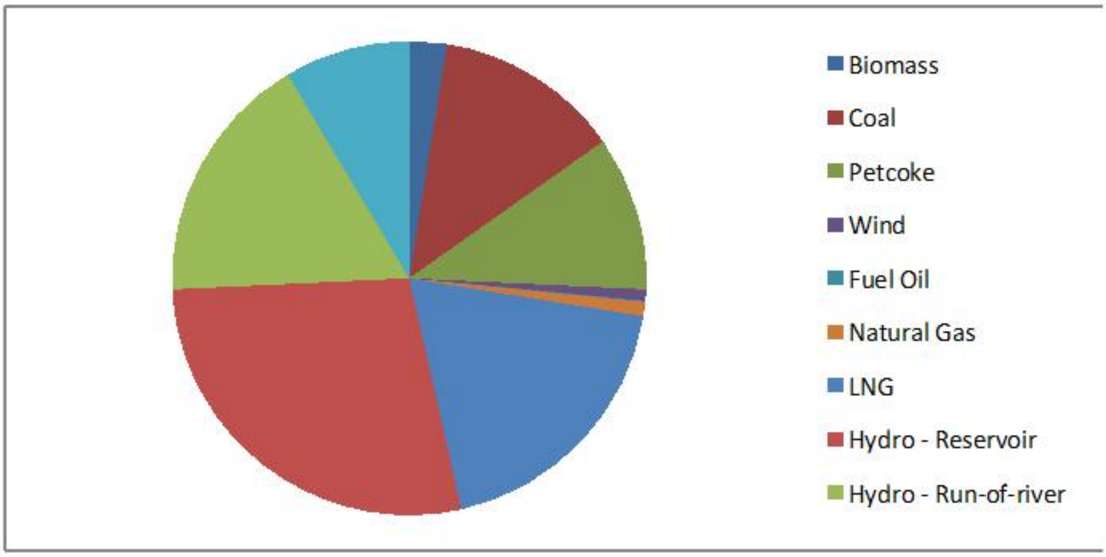
Primary Energy Source	2010	2011	2012	Average
Biomass	0,0%	0,0%	0,0%	**0,00%**
Coal	48,5%	69,6%	82,5%	**66,87%**
Petcoke	9,4%	0,2%	0,4%	**3,35%**
Wind	0,0%	0,0%	0,0%	**0,00%**
Fuel Oil	2,6%	1,8%	1,2%	**1,86%**
Natural Gas	26,8%	25,8%	13,6%	**22,08%**
LNG	0,0%	0,0%	0,0%	**0,00%**
Hydro – Reservoir	0,0%	0,0%	0,0%	**0,00%**
Hydro – Run-of-river	0,4%	0,4%	0,5%	**0,41%**
Petcoke	0,0%	0,0%	0,0%	**0,00%**
Diesel	12,4%	2,1%	1,6%	**5,37%**
Solar	0,0%	0,0%	0,0%	**0,00%**
TOTAL	**100%**	**100%**	**100%**	**100%**



64 Comisión Nacional de Energía. *"Generación Bruta SIC – SING"*. 2013. Retrieved from http://www.cne.cl/images/stories/estadisticas/energia/Electricidad/generacion_bruta_sic_sing.xls

3.1.2.- SIC ELECTRICITY GRID COMPOSITION

Primary Energy Source	2010	2011	2012	Average
Biomass	1,9%	1,9%	3,7%	2,54%
Coal	9,9%	11,7%	16,4%	12,68%
Petcoke	10,5%	11,0%	10,2%	10,55%
Wind	0,8%	0,7%	0,8%	0,75%
Fuel Oil	0,0%	0,1%	0,1%	0,09%
Natural Gas	2,5%	0,2%	0,1%	0,97%
LNG	14,4%	21,6%	20,7%	18,91%
Hydro – Reservoir	30,6%	28,0%	24,7%	27,76%
Hydro – Run-of-river	18,5%	16,7%	16,4%	17,19%
Petcoke	0,0%	0,0%	0,0%	0,00%
Diesel	10,8%	8,1%	6,9%	8,58%
Solar	0,0%	0,0%	0,0%	0,00%
TOTAL	100%	100%	100%	100%



3.2.- DATA FOR OTHER PV SYSTEMS

The following data, used as comparison for EPBT and GHG emissions rates, was obtained from Peng et al[65].

Author	Location	Irradiation	Location/Irradiation [kWh/m2/yr]	Module efficiency	Life time [yr]	PR	EPBT [yr]	GHG emissions rate [g CO2-eq./kWh]	Remarks
Ito and Komoto	China	1702	China/1702	N/A	N/A	0,78	2,1	50	Very-large scale PV systems installed in desert
Kato	Japan	1430	Japan/1430	0,103	20	0,81	1,7	14	Frame, 10 MW production scale
Raugei and Bargigli	South-European	1700	South-European/1700	0,09	20	0,75	1,5	48	Frame
Alsema and Wild-Scholten	South-European	1700	South-European/1700	0,09	30	0,75	1,1	25	Ground-mount system, U.S. production, frameless
Fthenakis and Kim	U.S.	1800	U.S./1800	0,09	30	0,8	1	23,6	Frameless
Wild-Scholten	South-European	1700	South-European/1700	0,109	30	0,75	0,84	16	Frameless, on-roof installation
Fthenakis	South-European	1700	South-European/1700	0,109	N/A	0,8	0,79	18	Ground mounted module
This study	North-Chile1	2533	North-Chile1/2533	0,127	30	0,8	0,6	12,2	Ground mounted module, adjusted angle, installed in desert. SIC electricity grid
This study	North-Chile2	2537	North-Chile2/2537	0,127	30	0,8	0,4	12,3	Ground mounted module, adjusted angle, installed in desert. SING electricity grid

[65] Peng, J., Lu, L., & Yang, H. (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255-274

3.3.- GHG EMISSIONS RATES FOR DIFFERENT ELECTRICTY SOURCES

The following electricity sources GHG emissions rates were obtained from Ecoinvent background processes and World ReCiPe Midpoint (H) v1.06 characterization factors. North Chile1 and North Chile 2 are the ones calculated at section 2.2.2.-

Electricity Source	GHG Emission rates (g CO2 eq/kWh)	Ecoinvent Background process
Coal	1080	Electricity, hard coal, at power plant/UCTE U
SING	996	Electricity, medium voltage, production SING - CHILE 2010-2012, at grid/CL U
Gas	642	Electricity, natural gas, at power plant/UCTE U
UCTE	531	Electricity, medium voltage, production UCTE, at grid/UCTE U
SIC	475	Electricity, medium voltage, production SIC - CHILE 2010-2012, at grid/CL U
Biowaste	147	Electricity, biowaste, at waste incineration plant, allocation price/CH U
North-Chile2	12,3	-
North-Chile1	12,1	-
Wind	11,2	Electricity, at wind power plant/RER U

Study Report

First Solar CdTe Module Technology and Environment Impact Assessment

Paper One

Lifecycle Assessment of First Solar CdTe Modules –Safety and Energy Output

Table of Contents

0. Introduction

A peer review was conducted under the leadership of China Renewable Energy Society and was funded by First Solar Inc. The purpose of this project was to comprehensively evaluate lifecycle environment, health and safety (EHS) impacts and energy output of First Solar's CdTe PV modules. The expert panel was composed of five experts from the Institute of Electrical Engineering of the Chinese Academy of Sciences, a national-level research institution, and All-China Environment Federation, a cause-oriented civil organization under auspice of the Chinese Ministry of Environment Protection, none having direct interest relation with First Solar. The two experts from the Institute of Electrical Engineering focus on research of compound films, crystalline silicon PV modules and materials, while the other three experts from All-China Environment Federation demonstrate proven expertise in environment impact assessment.

The project report comprises of two parts. This part, Paper One, assesses the lifecycle safety and energy output of CdTe modules. The second part assesses the environment, health and safety (EHS) aspects of CdTe modules. Inputs available to this research project include:

i) Published third-party research papers related to CdTe's lifecycle EHS and unpublished in-house statistics furnished by First Solar concerning CdTe modules' potential EHS risks and energy yield characteristics.

ii) Site tour to First Solar's plant in Kulim, Malaysia and communications with executives of the facility, covering:

- CdTe module production and recycling processes;
- Module quality reliability lab;
- In-house wastewater treatment facility;
- Debriefing on First Solar's EHS efforts.

First Solar ensures authenticity and validity of all the data provided by it.

1. Lifecycle assessment of safety of CdTe modules

1.1 Toxicological analysis

For a long time, researchers have referred to cadmium, a toxic element that may cause liver and kidney damage, or itai-itai disease as a result of calcium loss from body, and even cancer in cases of long-term contact, when studying toxicity of CdTe. A compound of cadmium that is insoluble in water, CdTe features maximum stability and very high bond energy and may react with acid. Its melting point is 1,041℃. However, basic data about its solubility in various acid solutions at different pH values are limited (S.Kaczmar, 2011). In fact, the so-called “read-across” approach is the most prudential method to judge toxicity of CdTe from cadmium. However the result might not be justifiable for this compound as physical, chemical and toxicological properties of CdTe have been proven to be much different to cadmium and other cadmium components.

CdTe is very stable. Table 1 compares it with several other Cd compounds. Cd, and such Cd compounds as $Cd(OH)_2$ and $CdCl_2$ are carcinogenic. But there are no research findings on carcinogenicity of CdTe.

Zayed and others (Zayed. J, 2009) evaluated acute inhalation and oral toxicities of CdTe in rats and found the median lethal concentration and dose to be three orders of magnitude higher than that of Cd. Prior testing by Chapin (1994) showed no detectable effects of CdTe on male or female rat reproduction. In-depth research on toxicity of CdTe by S. Kaczmar (2011) came to the following conclusions: no mutagenic activity causing genetic mutation was found in CdTe during bacterial reverse mutation test which compares to positive mutagenicity results for Cd (Ochi and Ohsawa, 1983; Oberly et al., 1982). The bioavailability of CdTe was evaluated with a simulated gastric fluid (pH of 1.5) and yielded 11 mg of cadmium per g of cadmium telluride (~1%) which compares to a read-across value of 100% for cadmium chloride. Acute toxicity was evaluated for Zebra fish at the limit of solubility for CdTe, and there was no toxic effect (fatal or indirectly fatal) on fish. Overall, CdTe is differentiated from Cd, showing low toxicity in the fields above.

Table 1 Comparison of several Cd compounds (V.M. Fthenakis 2004)

Compound	Temperature(melting point, ℃)	Temperature(boiling point, ℃)	Solubility (g/L)	Carcinogenic
Cd	321	765	Insoluble	Yes

$Cd(OH)_2$	300	–	2:6 x10^{-3}	Yes
CdTe	1,041	–	Insoluble	Unknown
CdS	1,750	–	1x10^{-3}	Possible
$CdCl_2$	568	960	1400	Yes

From the table above we can see that physical properties and toxicology of CdTe is obviously different from those of elemental Cd. So they should be treated differently. It should also be noted that there is no research data and findings on human-related toxicology and carcinogenicity of CdTe.

1.2 Safety in CdTe module production

1.2.1 Safety of staff under normal operation

Two of the core principles at First Solar are "Safety First" and "People Matter". Since the first day of CdTe module production, the company has developed strict management measures to prevent the impact of Cd compounds on staff and the environment during production. FS ensures safety of the working environment by monitoring content of Cd in the air frequently. Routine medical monitoring is performed on workers who have the potential to be exposed to Cd containing dust. Employee medical monitoring data for over a decade shows that the employees' blood cadmium and urine cadmium[1] level is far below the limit.

Production of CdTe modules has the potential to bring Cd-containing dust into the air. In their field study at First Solar's facility in Kulim, Malaysia, the experts observed that air pollution control equipment is used to ensure containment. Production processes are supported by local exhaust ventilation equipped with High Efficiency Particulate Air (HEPA) filters to ensure Cd dust is not emitted into the work environment. During equipment cleaning and maintenance, FS equips its staff with HEPA filter cartridges to protect them from cadmium dust. Many countries and organizations set occupational exposure limits (OEL[2]) (Table 2) for Cd exposure. FS adopts stricter standards than local OEL and provides necessary actions that must be taken when content of total cadmium

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[1]Urine cadmium level indicates the effect of long-term cadmium exposure, blood cadmium shows the impact of short-term cadmium exposure. β-2 microglobulin level is a secondary indictor. Presence of low molecular-weight proteins (such as β-2 microglobulin) excretion marks abnormal renal function.

[2]OEL (occupational exposure limit): Limit of Cd content in the air to which workers may be exposed without wearing respiratory protection appliances during a certain period of time (time-weighted average)

or small Cd particles in the air reaches 1.0 μg/m^3 and 0.8 μg/m^3 respectively.

Table 2 Occupational exposure limit (OEL) for Cd exposure

	U.S.	US-ACGIH(American Conference of Governmental Industrial Hygienists)	Malaysia	First Solar
8 hours OEL(total cadmium[3])	5μg/m^3	10μg/m^3	10μg/m^3	5 μg/m^3
12 hours OEL(total cadmium)	2.5μg/m^3	5μg/m^3	5μg/m^3	2.5 μg/m^3
Threshold above which measures must be taken (total cadmium)	2.5μg/m^3 8h 1.25μg/m^3 12h	N/A	N/A	1.0 μg/m^3
8 hours OEL(small Cd particles[4])	N/A	2μg/m^3	2μg/m^3	2 μg/m^3
12 hoursOEL(small Cd particles,)	N/A	1μg/m^3	1μg/m^3	1 μg/m^3
Threshold above which measures must be taken (small Cd particles)	N/A	N/A	N/A	0.8 μg/m^3

Kulim plant in Malaysia monitors Cd content in the air, including the data measured at specific positions and by air collectors fixed on workers working for 8 or 12hours. Average content measured at specific positions in the plant is below 0.16 μg/m^3(Fig. 1) constantly, and significantly lower than the threshold 1 μg/m^3 above. The results from air collectors show that Cd exposure risks of different steps are different, the highest during semiconductor deposition and

[3]Cd particles of all size
[4]Cd particles smaller than 10 μm

$CdCl_2$ spraying and curing oven, reaching nearly 0.5 µg/m^3, but still far below FS's threshold (Fig. 2).

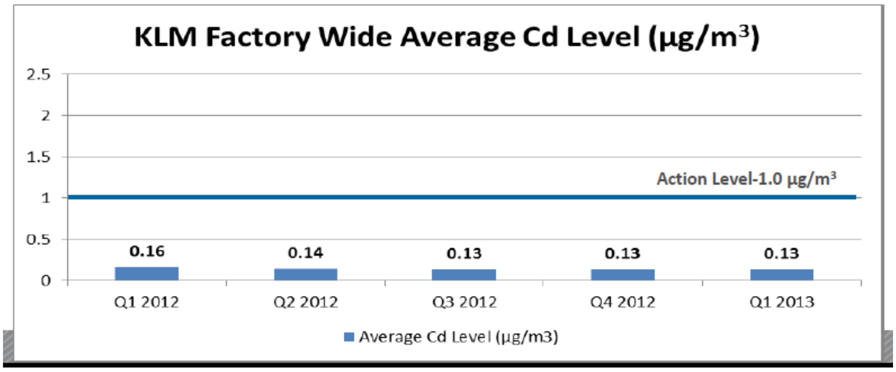


Fig. 1 Average historic Cd content in Kulim plant (provided by First Solar)

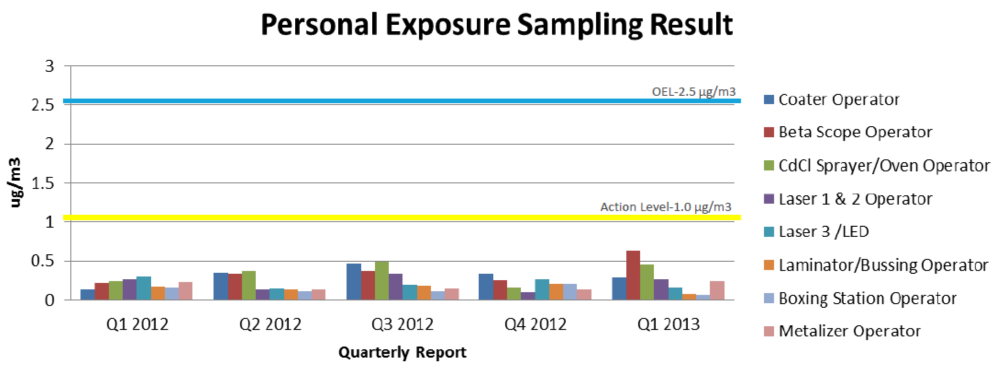


Fig. 2 Exposure sampling result of different steps in Kulim plant (provided by First Solar)

The only manufacturing activity that FS has recorded in excess of the 5 µg/m^3 is maintenance to the semiconductor deposition equipment (John R. Bohland, 2000). The First Solar high-speed vapor transport deposition process has a high semiconductor utilization rate but it is currently not possible to direct 100% of the inputted material to the glass substrate. With time, parts of the deposition chamber accumulate a small amount of CdS and CdTe semiconductors and must be cleaned. The cleaning staff wear respiratory protection appliances equipped with HEPA filter cartridges to protect themselves from inhaling cadmium-compound dust during these maintenance activities.

Fig. 3 Semiconductor deposition equipment maintenance (provided by First Solar)

FS has data of biological employee tests for over 5 years, which are completed by a third party[5]. Malaysia's national Occupational Safety and Health Administration (Malaysia OSH) provides content limit of blood and urine cadmium in employees of 5 μg/L and 3μg/g creatinine respectively[6].

FS tests blood and urine cadmium content in employees regularly. Kulim plant monitored blood and urine cadmium levels of over a thousand employees from 2007 to 2012, finding that the value is far below the limit set by OSHA(Fig. 4). It is important to note that statistics of 2011 and 2012 are not available for this Report because they are still being processed.

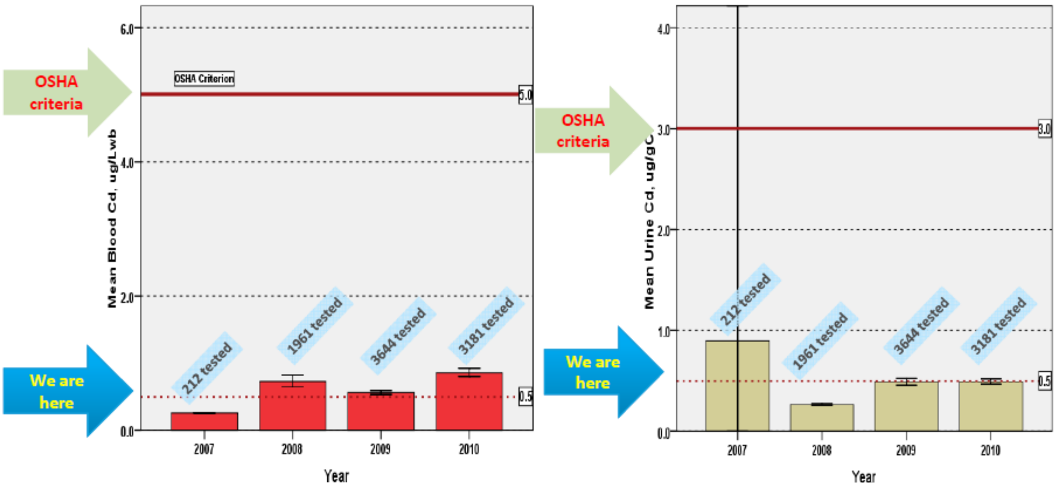


Fig. 4 Average blood and urine cadmium levels of the employees in Kulim plant (provided by FS)

Fig. 2 above shows that semiconductor equipment maintenance and

[5]Universiti Sains Malaysia Centre for Advanced Analytical Toxicology Services (CAATS)
[6]Limits set by Malaysia: blood cadmium 5μg/L, urine cadmium 3μg/g (creatinine).

$CdCl_2$spraying and curing oven workers are exposed to the environment with the highest Cd content. The two monitoring results from blood and urine cadmium samples of several such workers picked by Kulim plant are both far below the set limit (dotted line in blue).

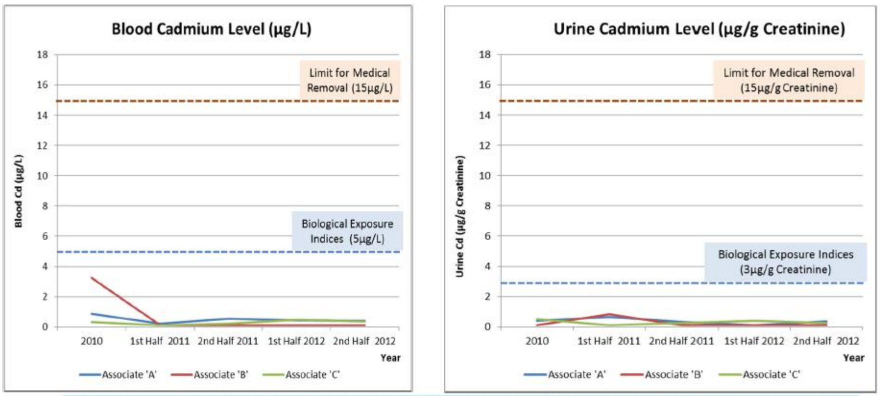


Fig. 5 Blood and urine cadmium levels of semiconductor equipment maintenance workers (provided by FS) obtained semiannually.

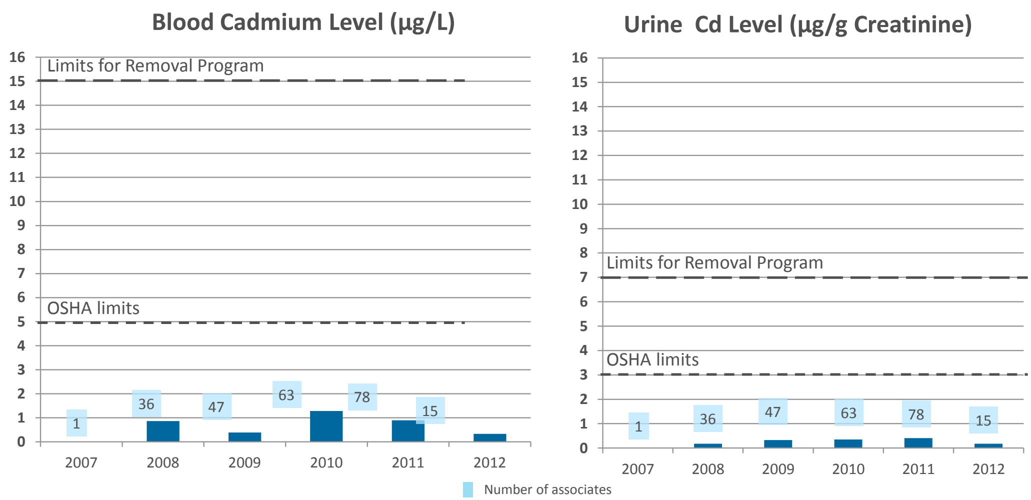


Fig. 6 Blood and urine cadmium levels of $CdCl_2$ curing oven workers (provided by FS) obtained annually prior to 2012 and triennially beginning 2012.

In addition, FS' ongoing monitoring shows that smoking cigarettes increases Cd content in the human body. FS compares blood and urine cadmium levels in smokers and non-smokers prior to (1,253 persons) and after (2,458 persons) employment, and finds that blood cadmium level in smokers is apparently higher than that in non-smokers, but there is no obvious difference between blood and urine cadmium levels prior to and after employment.

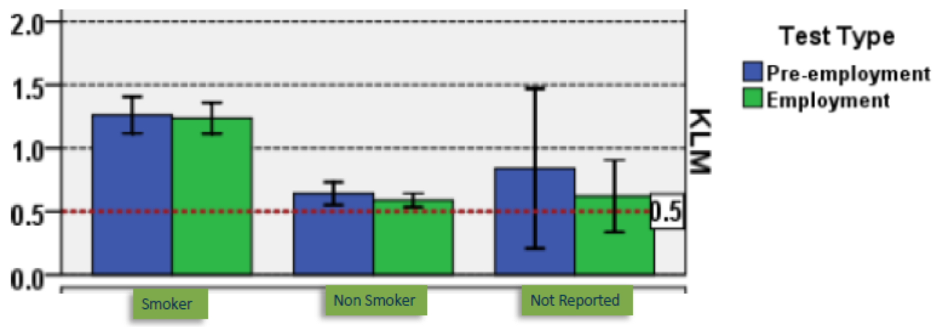


Fig. 7 Comparison of blood cadmium level in smokers and non-smokers prior to and after employment (provided by FS)

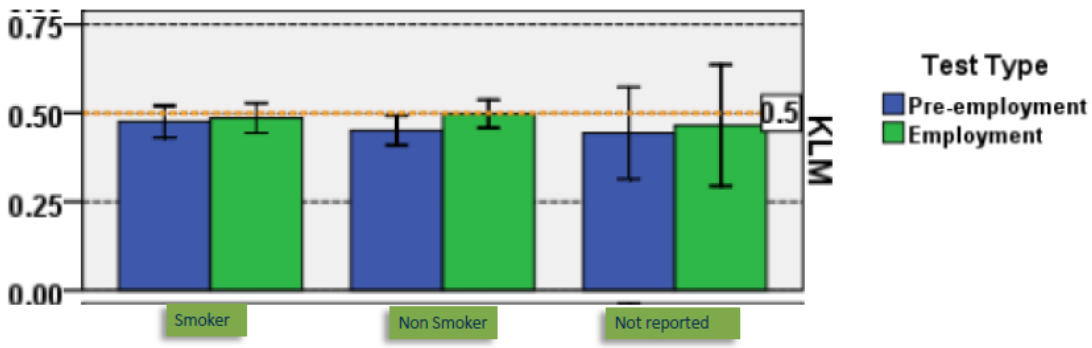


Fig. 8 Comparison of urine cadmium level in smokers and non-smokers prior to and after employment (provided by FS)

1.2.2 Safety of staff in case of emergency

Potential safety risks that need to be managed by FS CdTe module production plants include potential exposure to cadmium compounds used in manufacturing. Since cadmium compounds are deposited mainly in airtight vacuum chambers, exposure is unlikely to happen during normal production and operation. This is determined by physical properties of CdTe and is supported by the data gained from KLM. When the temperature in the vacuum environment is higher than 300°C, CdTe will change from solid state directly to gaseous state. But when the temperature is lower than 300°C, or the ambient pressure rises, the sublimation process will weaken until condensation, and CdTe will come back to solid state rapidly. Saturated vapor pressure of CdTe at 150°C is 10^{-11} Pa only. It's impossible for CdTe to exist in gaseous state under normal temperature and pressure. These physical properties make production of CdTe thin-film safe. Once the vacuum or high-temperature environment is damaged, CdTe vapors will condense to solid particles, which will stay on the wall of chamber or pipe; it will not spread in gaseous state, further limiting any potential human exposure. First Solar also uses HEPA filters on all equipment that has the potential to generate Cd containing dusts to ensure Cd levels are controlled to well below the FS action level. Before usage, FS will detect leakage of each filter to ensure its normal operation. For accidents, FS developed a complete Cd leakage treatment measure package to minimize the possible impact of Cd on human body and the environment. First Solar also uses HEPA filters on all equipment that has the potential to generate Cd containing dusts to ensure Cd levels are controlled to well below the FS action level. First Solar leak-checks each HEPA filter prior to use to confirm that the filter is functioning properly. To ensure workplace safety, FS also developed safety codes for accidental injury, fire, power and chemicals. FS holds OHSAS18001 certificate.

1.3 Safety in CdTe module usage

1.3.1 Safety under normal operation

CdTe modules release no vapor or dust under normal conditions because CdTe features high melting point, low saturated vapor pressure and is insoluble in water. The CdTe semiconductor material is well encapsulated between two 3-mmsheets of glass and a layer of industrial laminate until the end of the lifecycle, and is very unlikely to be exposed to the outside environment. Such encapsulation option is required to ensure performance and stability of products, rather than by environmental protection regulations. Therefore, CdTe modules will not emit any Cd compounds under normal operation.

1.3.2 Safety in case of foreseeable accidents

Possibly, Cd exposure during normal usage of CdTe modules may happen in case of accidents. This Report reviews the research findings on the potential for cadmium compounds to be released from CdTe modules when fire happens or modules crack.

Brookhaven National Laboratory studied the impact of fire on CdTe modules with double glasses under certain conditions (V. M. Fthenakis, 2005). In the test, modules were cut into samples with size of 25×3 cm. In accordance with American Society for Testing and Materials(ASTM)'s "Fire Tests of Building Construction and Materials (E119-98)" and the "Standard for Fire Test of Roof Deck Constructions (UL 1256)" of U.S. Underwriters Laboratories(UL), the samples are exposed to the environment of 760~1,100℃ for 30 minutes to 3hours. Most of Cd diffuses into the glass in such test (Fig. 9). Only little (0.4~0.6 percent of the Cd content) Cd was released into air (Table 3). The small Cd loss occurs from the edges of the PV module through the space of the two glass sheets [7] before they fuse together. In PV modules of actual size, since the ratio of perimeter to area is smaller than our samples, the actual Cd loss during fires will be extremely small (<0.04% of the Cd content).

Table 3 Loss of mass of tested samples at different temperature

Test	Temperature(℃)	Weight loss((% sample)	Cd emission		Tellurium emission	
			(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

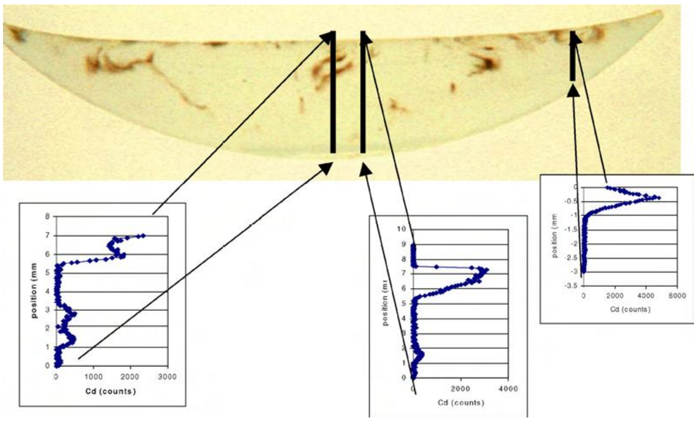


Fig. 9 X-ray fluorescence microprobe analysis–vertical slice from middle of sample heated at 1100˚C; Cd counts in the center and the sides of the slice

Bavarian Environmental Protection Agency calculated distribution of Cd released during fire with VDI3783 air dispersion model (Beckmann and Mennenga 2011). The highest determined value is – as expected – in a fire with the largest area (1,000 m^2) with the maximum cadmium module contents which have been found in literature and are several times higher than those of

[7]FS modules have two sheets of glass

FS' CdTe modules (66.4 g/m^2) and at the shortest calculable distance (100 m) from the emission site assuming in the calculations that all cadmium contained in the module is released completely from the CdTe compound as cadmium fumes. However, the calculated concentration of cadmium (0.66 mg/m^3) is still substantially below the AEGL-2[8]Cd evaluation values. A serious danger for the immediate neighborhood and general public can certainly be excluded when modules containing CdTe burn.

Module breakage is rare, occurring in approximately 1% (average: 0.04 percent/year) of modules over the 25-year warranty operating life (Sinha, P., Balas, R., et al, 2012). Of these breakages, over one-third occurs during shipping and installation and is removed for takeback and recycling. 80 percent of such breakage is caused by glass internal stress and impact. FS confirms that such breakage consists of glass fracture in most cases because laminated materials are used between the two sheets of glass. Such fractures are very small, so potential CdTe exposure area is very small too.

While unlikely, it is possible for CdTe in modules to enter soil along with rain and be released into air by dust if module breakage is not discovered or takeback measures are not taken in a timely manner. Sinha P.(Sinha, P., Balas, R., et al, 2012) evaluated potential exposures to Cd from rainwater leaching of broken CdTe thin-film cells in a commercial building scenario by analyzing Cd destination and transfer mechanism. In this analysis, an average breakage rate of 0.04%/year is applied. The evaluation considers the worst-case scenario in which the total mass of Cd in each broken module is released. Leaching from broken modules is modeled and residential screening levels are used to evaluate potential health impacts to on-site workers and off-site residents. Potential exposures to Cd from rainwater leaching of broken modules in a commercial building scenario are highly unlikely to pose a potential health risk to on-site workers or off-site residents.

1.4 Safety in end-of-life disposal of CdTe modules

CdTe modules abandoned several years after end of their 25-year quality warranty period, during the warranty period due to various reasons and during production because of non-conforming quality need to be disposed of properly. Available options include: landfilling, incineration or recycling.

According to the results of U.S. EPA Toxicity Characteristic Leachate Procedure (TCLP) (Wegmann, 2011), Cd with leaching level of less than 1 mg/L may be treated as non-hazardous waste. For this TCLP test, the CdTe

[8] AEGL: Acute Exposure Guideline Level. AEGL-2 refers to the level that will lead to irreversible or serious physical damage to general people.

modules were broken into 1 cm fragments which were agitated in a mixture of sodium acetate/acetic acid (pH 2.8-4.93) (note that nitric acid/sulfuric acid solution is required by China) for 18 hours. FS has no hazardous waste leaching test results for China. CdTe modules incinerated will release 5 g/kg of Cd ideally, and the remaining Cd will be encapsulated in fused glass, no longer contaminating the environment (Marco Raugei, 2012).

In 2005, FS established a complete recycling mechanism for the end-of-life CdTe modules, the first comprehensive pre-paid collection and recycling system in the industry. Under this program, after the 25-year warranty service life ends, the modules will be taken back, the glass sheets separated to take out the metal and semiconductors in the middle. The recovered materials will be reused to manufacture new products. All the pre-payment, covering all the cost needed to dismantle, gather, transport and recycle end-of-life CdTe modules, by a third party audited and supervised by an independent third party. In addition to the pre-funded recycling option which has historically been provided, recycling can also currently be funded through recycling service agreements. In the European Union under the WEEE Directive, recycling for Business-to-Consumer PV sales is expected to be funded with a joint liability scheme in which PV manufacturers contribute to a joint fund for collection and recycling as well as insurance to cover the case of bankruptcy. Note that the WEEE Directive distinguishes between Business-to-Consumer and Business-to-Business transactions when mandating effective financing mechanisms. Under the latter, recycling is expected to be financed through contractual agreements between the businesses. It is believed that in China, the Business-to-Consumer transaction under supervision of the government or industry association is a more viable option.

FS has a mature recycling process, which is shown in Fig. 10 below.

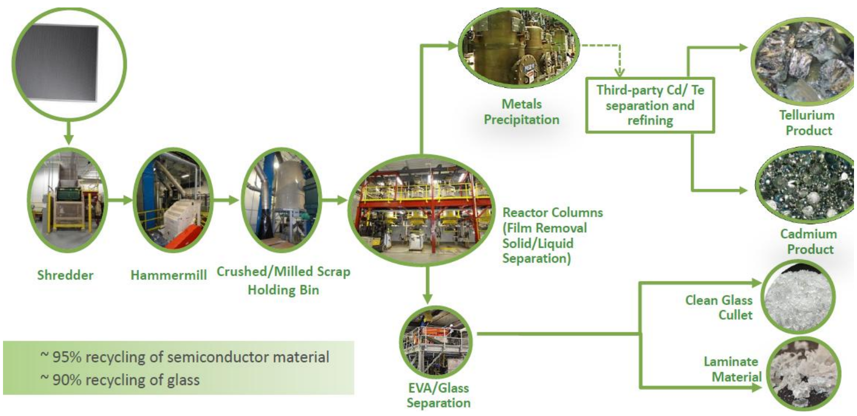


Fig. 10 FS CdTe module recycling process

i) End-of-life modules or the modules broken or deemed non-conforming during production are delivered to the recovery plant.

ii) Shredder: Putting modules into the shredder.

iii) Hammermill: Use the hammermill to grind crushed modules 4-5mm fragments to enable subsequent reaction.

iv) Holding bin

v) Reactor column: Putting the fragments into column reactor. Adding strong acid to make sure semiconductor materials in modules fully react with acid. Separating the solid (EVA and glass) from the liquid (metal-rich acid solution).

vi) Metal precipitation: Pumping the liquid into the liquid tank for three steps of precipitation;

vii) Refining by third-parties: Filter pressing the metal precipitated into Cd or tellurium-rich cakes and delivering them to third-parties for Cd and tellurium refining. Up to 95 percent of metal is reused.

viii) EVA/glass separation: Separating EVA from glass

ix) Glass recycling: Cleaning and drying glass. Nearly 90 percent of glass is recycled by third-parties to produce new glass.

x) EVA collection: Collecting EVA and disposing of it according to local waste disposal standards.

Module recycling recovers most of the mass of modules, including about 95 percent of CdTe and about 90 percent of glass. Recycling of tellurium and Cd reduces the impact of Cd release on the environment and ensures safety of modules after their lifecycle to the environment.

Furthermore, FS module recycling brings many other benefits: i) Reducing the land occupied by landfills and incineration pollution; ii) Lowering lifecycle energy consumption and GHG emissions of CdTe PV (Sinha, P., M. Cossette, et al, 2012); iii) alleviating the imbalance between tellurium (scarce resource) supply and demand in future (M. Marwede and A. Reller, 2012).

FS uses complete precautions for module recycling, including HEPA filter cartridges and acid gas spraying and scrubbing device, as well as plants' wastewater treatment system discharging effluent meeting local discharge standards. So there will be no Cd pollution during recycling process under normal circumstances.

1.5 Lifecycle Cd emission of CdTe modules

Lifecycle of Cd in CdTe modules includes zinc mining, Cd refining, CdTe production, CdTe module production, CdTe module operation, end-of-life CdTe module disposal.

According to Fthenakis (Fthenakis, 2004), of the Cd emission during zinc mining and smelting, 0.58 percent of the total may be attributed to Cd.

According to the research findings of Fthenakis (Fthenakis, 2004), Cd refining and CdTe production are patented technologies possessed by only several companies. It is shown that the Cd dust generated is processed by HEPA filter cartridges before being released into air (6g/t).

FS adopts many measures during module production and recycling to ensure Cd emissions are far below the national standard, minimizing potential Cd pollution risks. FS' CdTe module production uses Vapor Transport Deposition to deposit CdTe and CdS thin-films in airtight chambers, depositing a layer of CdTe that is thinner than 3 micron. There is only 6g of Cd in a whole module (0.72 m^2) (Sinha, P., Balas, R., et al, 2012). Cd-containing exhaust gas generated during production is treated by HEPA before being emitted, which filters out up to 99.97 percent of 0.3-μm dust that is the most difficult to be filtered. So only 0.4 mg/kg of Cd is released into air (Raugei and Fthenakis, 2010). Cd ion in Cd-containing wastewater from production line is removed in the wastewater treatment works through metal precipitation and ion exchange methods. Concentration of Cd in Cd-containing wastewater is monitored prior to discharge through ICP method. The wastewater meeting discharge standards may be discharged. In the rare case when wastewater does not meet the discharge standard it is returned for re-treatment. The concentration value is 0.01~0.015 mg Cd/L under normal production conditions, far below the value set by Malaysian government , which is 0.02 mg/L.

First Solar generates small quantities of hazardous (solid) waste from disposal of cadmium contaminated personal protection devices and maintenance of process filtration equipment (John R. Bohland, 2000). In a large-scale production factility, hazardous wastes also include sludge generated in waste water disposal. The wastes will be disposed of in accordance with the national standards for disposal of hazardous wastes. CdTe wastes generated during maintenance of deposition chamber will be delivered to third-parties for recycling of tellurium and Cd.

1) Direct release of Cd into air

According to the research findings of Fthenakis (Fthenakis, 2004), using 1 ton of Cd in the manufacturing of CdTe PV modules releases 15.25g of Cd into the air throughout the entire lifecycle of the modules, and generating 1 GWh of power releases a total of 19.8mg, a very low level. See Table 4 for Cd emission into air of CdTe modules during the whole lifecycle.

Table 4 Cd emission into air of CdTe modules during the whole lifecycle

Process	Release into air (g Cd/ton Cd)	Contribution (percent)	Release into air		
			(g/ ton (Cd))	(mg/m^2)	(mg/GWh)
1. Zinc exploitation	2.7	0.58	0.0157	0.0001	0.02
2. Zinc smelting/refining	40	0.58	0.2320	0.0016	0.3
3. Cd refining	6	100	6	0.042	7.79
4. CdTe production	6	100	6	0.042	7.79
5. CdTe PV module production	3	100	3	0.021	3.9
6. CdTe module operation	0	100	0	0	0
7. End-of-life disposal/recycling of CdTe PV modules	0	100	0	0	0
Total			15.25	0.11	19.8

Assumptions:

1. Exploitation of one ton of zinc ore generates 30g of dust.

2. Smelting/refining of one ton of zinc generates 0.2g of Cd.

3. Ratio of zinc to Cd content in zinc ore is 200.

4. Average content of Cd in zinc ore is 220ppm.

5. HEPA filters could filter out up to 99.97 percent of submicron dust in exhaust gas from PV production.

6. Calculation of energy output of per unit of Cd is based on:

- Modules with 7g Cd/m^2

- 10 percent of photoelectric conversion efficiency (note that average efficiency in year 2012 is 12.7%)

- Average intensity in U.S. (1800KWh/m^2/year)

- 30years of expected service life of PV modules

- Therefore, 1kg of Cd generates 0.77GWh of power during the service life of PV products.

2) Direct release of Cd through wastewater

Table 5 summarizes discharge of Cd wastewater provided by Raugei (Raugei and Fthenakis 2010). Most of the Cd wastewater is generated during recycling.

Process	Zinc exploitation	Cd refining, CdTe processing, CdTe production	Operation	Recycling	Total
Cd discharge through wastewater	0	0.3mg/m^2	0	1 mg/m^2	1.3 mg/m^2

3) Direct release of Cd through wastes

Existing research findings on release of Cd through wastes are very limited. Raugei (Raugei and Fthenakis 2010) believes that no CdTe PV plant discharges Cd into soil now. In the opinion of Bohland (John R. Bohland, 2000), a small quantity of wastes are generated during disposal of cadmium contaminated personal protection devices and maintenance of process filtration equipment into approved landfills. In a large-scale production facility, this also includes sludge generated during waste water treatment. Howeve, the aggregate direct release is lower than 1,000 kg/month.

4) Comparison of life-cycle atmospheric Cd emission between CdTe PV systems and other technologies

Comparison of life-cycle atmospheric Cd emission (including direct and indirect emission) between CdTe PV systems and other technologies by Fthenakis (Fthenakis, 2008) shows that Cd emission by CdTe PV systems (0.3g Cd/GWh) is significantly less than that by oil-fired power plants (43.3gCd/GWh), coal-fired power plants (3.1g Cd/GWh), and even lower than mono-Si and multi-Si (0.9g Cd/GWh). Cd emission by oil and coal-fired power plants comes from the Cd in such fossil fuels, while emission by crystalline silicon technology from consumption of power from the grid generated with coal. It is important to note that direct Cd emission (0.02 g/GWh only) during the whole lifecycle of CdTe, including emission by material refining and synthesis, module production, operation and recycling, is significantly less than indirect emission (as high as 0.28 g/GWh), including that caused by power consumption during glass production, material encapsulation, BOS and module production. It should be noted that the data above is based on U.S.' reality, i.e., thermal power accounts for only 44 percent of the total output, while in China, this proportion will be higher, affecting the indirect emission value.

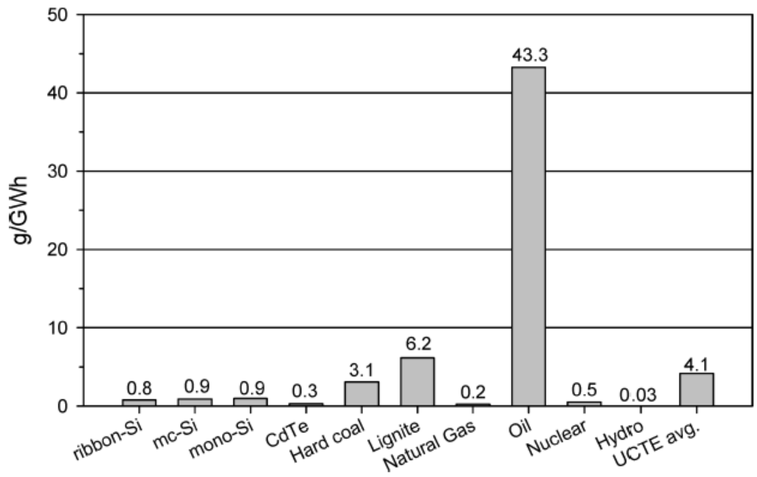


Fig. 11 Life-cycle atmospheric Cd emission of different power generation technologies (energy output: 1,700KWh/m^2/year, system efficiency: 0.8, service life: 30years, indirect Cd emission caused by BOS considered)

2. Benefits from CdTe PV module usage

2.1 Generating power with CdTe PV modules is an effective way to control Cd pollution

Cd is mainly generated during zinc production. Because yield of zinc is very large, output of Cd, as by-products, is also very impressive. Such Cd needs to either be used in other places or disposed of as required by the government.

General disposal method is landfilling by cementing. The most ideal use is low-consumption [9] applications, creating added value while reducing Cd emission risk. CdTe PV modules may be regarded as low-risk, sustainable and ideal application because: i)CdTe PV modules are low-consumption Cd application. Cd is converted to CdTe, a stable compound, then completely encapsulated during operation and recycled at the end of lifecycle (FS established a complete CdTe module recycling mechanism); ii)Such modules have less impact on the environment than other applications. Among the four major Cd applications (nickel-cadmium rechargeable battery: 82 percent, pigment: 10 percent, electrofacing: 6 percent, stabilizer for plastics: 1.5 percent)(UNEP, 2006; ICDA, 2005), CdTe PV modules and nickel-cadmium battery are low-consumption Cd application (Cd in nickel-cadmium batteries could be 100 percent recycled in principle). Pigment, electrofacing and stabilizer are high-consumption Cd application, where Cd will dissipate and inevitably cause Cd pollution. Compared with nickel-cadmium batteries, CdTe in CdTe modules is more stable than $Cd(OH)_2$ in nickel-cadmium batteries in terms of solubility, melting and boiling points. In addition, CdTe modules are larger than nickel-cadmium batteries, easier to be disposed of at the end of lifecycle; iii) Last but not least, CdTe modules convert solar energy into power, reducing consumption of conventional energy sources and lowering Cd emissions produced by conventional power generation technologies (such as thermal power).

2.2 Industry-scale application of CdTe PV modules is feasible;

2.2.1 CdTe modules have the lowest life cycle carbon footprint and fastest energy payback time

Peng (Peng, 2013) summarized lifecycle research on different PV technologies in the past, finding that all researchers hold the same view that lifecycle carbon emission by PV technologies is an order of magnitude smaller than that of fossil-based electricity. Among the five common PV technologies (mono-Si, multi-Si, amorphous silicon, CdTe, CIS), CdTe modules presents the best environmental performance in terms of energy payback time (0.75 - 2.1 years only (Fig. 13)) and carbon emission rate (generally between 14 to 35g CO_2/kWh (Fig. 12)) due to its low life-cycle energy requirement and relatively high conversion efficiency. See Fig. 12 and Fig. 13 for comparison between CdTe and other PV systems in terms of GHG emission and energy payback time.

[9] Low-consumption Cd application: The degree of Cd dissipation into the environment is very low, Cd in products could be recycled effectively

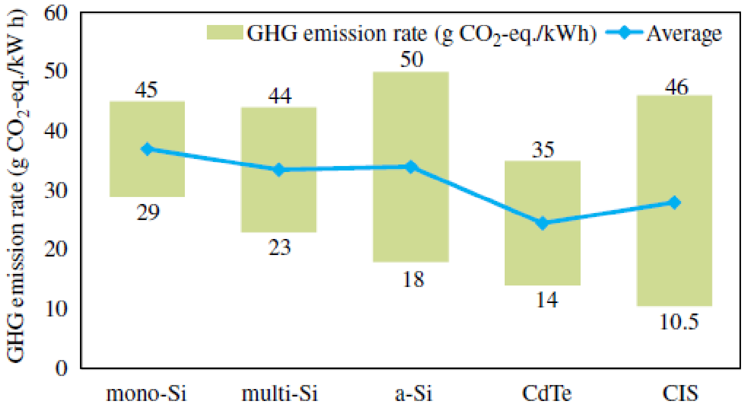


Fig. 12 GHG emission rate of different PV systems

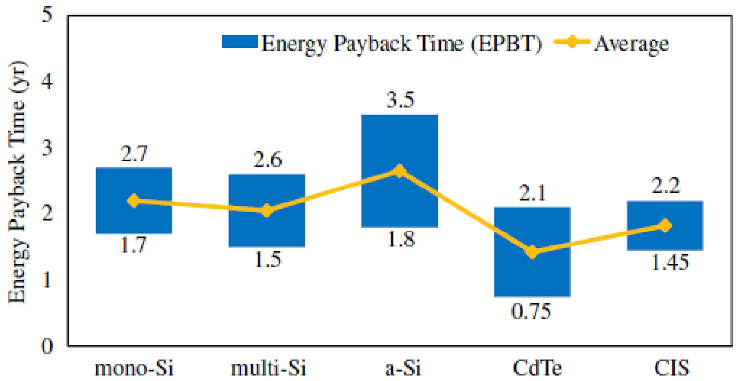


Fig. 13 Energy payback time of different PV systems

2.2.2 Excellent in quality and reliability

FS has done a lot of work to ensure reliability of CdTe modules, which have passed International IEC61646 test, North American UL1703 test and Chinese Golden Sun test.

According to Strevel (2012), a study made by the U.S. National Renewable Energy Laboratories (NREL) on efficiency degradation rates of five common PV modules (amorphous silicon, CdTe, CIGS, mono-Si, multi-Si) installed before and after 2000 shows (Fig. 14) that FS realized the lowest degradation rate for thin-film CdTe thin-film products installed after 2000 through technology improvement and strict production process control, 0.5-0.8 percent/year only, comparable to traditional crystalline silicon technologies (Strevel, N, 2012). The 17-year performance monitoring on a PV system in Golden, Colorado, USA by NREL reports a long-term degradation rate linear fit of –0.53%/year. After almost two decades of monitoring, NREL confirms the excellent reliability of First Solar’s module technology, with no module failures in system operation.

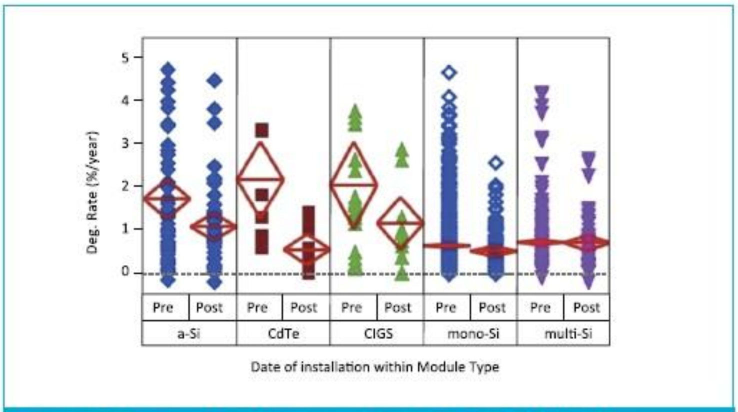


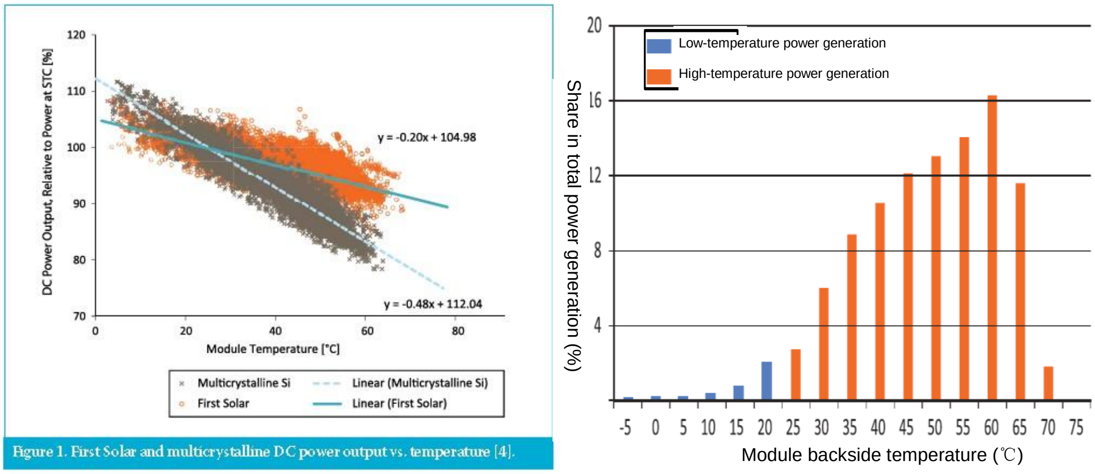
Figure 6. NREL study of degradation rates of various PV technologies [12].

Fig. 14 NREL study on long-term degradation rates of various PV technologies

2.2.3 Low temperature coefficient

First Solar's thin-film CdTe solar modules have a proven high- temperature performance advantage over typical crystalline silicon solar modules. The leading contributor to this performance advantage is the lower temperature coefficient [10] of CdTe semiconductor material, which delivers higher energy yields at elevated temperatures. Crystalline silicon solar modules typically have a temperature coefficient of –0.45 to –0.5% per degree Celsius. First Solar's CdTe PV modules have a temperature coefficient of –0.25% per degree Celsius, resulting in about half the incremental power loss compared to conventional solar modules. Fig. 15a shows the DC power of two PV systems consisting of CdTe and multicrystalline silicon (mc-Si) modules. As module temperatures rise above 25°C(Fig. 15b), CdTe solar modules experience an increasing performance advantage, which is relevant because in high-temperature climates the majority of solar energy production occurs when the module operating temperature is much greater than 25°C. Comparison performed by a major system integrator concluded that, in southern Italy (Strevel, N, 2012), CdTe modules outperformed mc-Si in annual specific yield by 5.7%.

[10]Temperature coefficient expresses the rate of reduction of power output as a function of module operating temperature rise.



a) b)

Fig. 15 a) First Solar and multicrystalline DC power output vs. temperature.

Fig. 15 b) Annual temperature distribution of power generation of CdTe modules in desert area.

2.2.4 Supply of tellurium could support massive production of CdTe modules.

Te, a humble nonmetal that is actually abundant in the universe, is rare in Earth's crust. The existing supply is obtained almost exclusively through Te recovery as a by-product of refining copper. We do not know the reserve of tellurium. If the market's demand for tellurium increases continuously, tellurium exploration will be stimulated. The annual supply is between 500 to 1,500 MT/year, which will increase with rise of copper demand, typically 3-5 percent/year.

CdTe modules' demand for tellurium is 90-130kg/MW (Zweibel.K. 2010). Current supply may produce 10 GW per year. But the following three factors will eliminate tellurium resource restrictions on the yield of CdTe modules: i) The annual supply will increase with rise of copper demand, typically 3-5 percent/year. In addition, many new bismuth telluride and undersea tellurium beds were discovered; ii) Module production technology is progressing, and there is space for improvement of module conversion efficiency. Thickness of CdTe in PV modules is likely to reduce from 3 μm to hundreds of nanometer, lowering Cd consumption per Wp; iii) As a large amount of modules reach the end of lifecycle, many tellurium resources in modules will be recycled. Conservative estimation shows that, by 2040, 10-50 percent of tellurium needed by CdTe module production will be met by such recovered resources (M. Marwede 2012). Considering improvement of module and tellurium recycling efficiency (97 percent of tellurium in abandoned modules is recycled, and 90 percent of it is refined to high-purity tellurium), by 2038, tellurium recovered from end-of-life modules will be likely to meet the demand of the whole CdTe PV industry (M. Marwede 2012).

3. Conclusions

1) **CdTe module is a promising PV technology.** CdTe PV technology is inexpensive and efficient. FS expressed that efficiency of its CdTe modules could reach 14.9 percent by the end of 2014, close to that of multi-Si modules, and the cost of CdTe modules may be lowered by 10 percent. Good quality, reliability, and temperature coefficient of CdTe enable CdTe modules to operate stably and efficiently during the 25-year lifecycle. Given the low lifecycle CO_2emissions and short energy payback time of CdTe PV, wide application may effectively help us realize the goal of energy conservation and emission reduction.

2) **CdTe is a very stable compound, less toxic than elemental Cd.** The experiment of acute inhalation and oral toxicities of CdTe in rats found that CdTe less toxic than elemental Cd. Acute toxicity was evaluated for Zebra fish at the limit of solubility for CdTe, and there was no toxic effect (fatal or indirectly fatal) on fish. Solubility and bioavailability of CdTe is significantly lower than other Cd compounds. So CdTe compound and elemental Cd shall be treated differently in terms of toxicity. It should be noted that there is no research data on the toxicity to the human and carcinogenicity of CdTe.

3) **FS manufacturing plant takes effective measures to ensure production safety.** First Solar has been adopting excellent management system processes and policies during module production and recycling to protect the environment and workers' health and safety. Actual Cd emissions into the atmosphere and water are well below Malaysia's limits. First Solar is very active in ensuring environmental safety and avoiding safety risks. First Solar plant has obtained ISO9001, ISO14001 and OHSAS18001 certificates.

4) **Modules have no or little impact on the environment and the surrounding population during operation.** CdTe will not escape from modules under normal operation. Existing research findings show that, in case of foreseeable accidents, such as fire, almost all (99.96 percent) Cd in CdTe will be encapsulated in glass, only 0.04 percent of Cd will go into air before the two glass sheets fuse together. Under average module breakage rate (0.04 percent/year), since CdTe is thin and in small quantity, even release of all Cd in modules is highly unlikely to pose a potential

health risk to on-site workers or off-site residents.

5) **FS' recycling measures and technologies ensure environmental safety of end-of-life modules.** First Solar has introduced an excellent module collection and recycling mechanism to recover CdTe PV modules from users reducing Cd pollution risk of end-of-life modules. Currently about 95 percent of Cd and tellurium could be recovered.

6) **Generating power with CdTe PV modules is an effective way to control Cd pollution.** Cd comes mainly from zinc and lead smelting. Even if CdTe PV modules have no demand for Cd, significant volumes of Cd will be released during zinc and lead exploitation and smelting every day. CdTe PV modules are an effective way to reduce Cd pollution risk because CdTe is the most stable among Cd compounds, and CdTe is well encapsulated in modules, which could be recycled by FS' recycling mechanism with 95% recovery at the end of the modules' lifecycle. Therefore, compared with other high-consumption Cd applications, CdTe modules are safer for the environment. Most of all, CdTe modules convert solar energy into power, reducing consumption of conventional energy sources and lowering Cd and other greenhouse gas emissions released by oil or coal-powered power generation.

7) Considering rapid progress of CdTe PV technologies and improvement of module efficiency after 2011, data in this Report might be inapplicable to new products launched by FS in future. The trend needs to be proved by many new research activities.

4. Suggestions

CdTe module is a competitive, low-cost and efficient PV technology. As long as necessary treatment measures are in place to control Cd pollution during the lifecycle of CdTe modules, it could generate power in a cleaner and more environmentally-friendly way than other PV technologies. Given that many typical Cd-polluted areas are seen in China, and the government and public pay close attention to the problem, we hereby put forward the following suggestions:

1) It is advisable that China includes CdTe, a competitive PV generation technology, into its 13th Five-year Plan as a commercial-scale PV technology, and improve its CdTe research and production technology level.

2) The PV Industry should establish a recycling and takeback mechanism for

China by reference to the mandatory mechanism for end-of-life PV module recycling to be enforced as of 2014 by EU WEEE. Such a mechanism is a necessary prerequisite for China to deploy CdTe PV modules and mitigate the risks of Cd contamination. In addition, ensuring enforcement of such mechanisms will strengthen the public's confidence in safety of the technology. FS is suggested to work with the Chinese government in this regard.

3) Since CdTe modules retire generally after 25years or a longer period of time, FS is suggested to share CdTe recycling technologies with China to make sure massive recycling of such modules in China is feasible technically after the 25-year period, so as to eliminate the concerns of the public and industry.

4) FS should carry out tests by referring to the Standard on Hazardous Waste Leaching Experiments and suggest relevant authorities to give effective disposal plans when the modules could not be recycled in light of the results.

5) Given that many regions see acid rain, CdTe leaching experiments should be carried out at different pH values to give CdTe handling suggestions to ensure environmental safety.

6) FS should disclose important data and literature to the public and academic community to guide them in treating toxicity and harm of CdTe and elemental Cd differently, and help them know how FS takes measures to control Cd emissions.

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First Solar CdTe PV Cell Technology and Environmental Impact Assessment Report

China Environmental United (Beijing) ENV. Protection CO.LTD

December 2013, Beijing

Paper Two

Environmental Impact Assessment and Suggestions for First Solar CdTe PV Cells

Contents

1 Analysis of CdTe PV cell pollutant migration patterns

Heavy metal migration and transformation refer to movement of the spatial position and transformation of the existing form in the natural environment and the resulting enrichment and dispersion process. Heavy metal migration and transformation in the environment are subject to impact and control of physical, chemical, biological and other factors.

CdTe's lifecycle consists of: (1) mining of zinc, lead, and copper ores, (2) Cd and Te as by-products of smelting/refining of zinc, lead, and copper, (3) purification of Cd and Te, (4) production of CdTe, (5) manufacture of CdTe PV modules, and, (6) recycling or disposal of end-of-life modules.

1.1 Analysis of CdTe PV cell migration pattern in water

This section considers the potential for CdTe to enter water bodies in the phases of mining of ores, purification and synthesis, and decommissioning and recycling. In the production phase, residual pollutants from treated process wastewater in CdTe PV cell manufacturing may enter water bodies. In the current vapor transport deposition-based manufacturing, the total Cd emissions from all manufacturing and recycling operations are 0.4 mg Cd/kg Cd. Including all the items in the lifecycle inventory of PV-module manufacturing, it's calculated here a total of 1.3 mg (Cd)/m^2 of module (Raugei and Fthenakis 2010). Virtually no emissions are associated with the operational phase, because cadmium in CdTe PV modules is present only as chemically stable cadmium compounds (i.e. CdTe and CdS) that are enclosed and sealed within two glass panes. Thus, we do not expect any emissions while the modules are in use Even in accidental fires, CdTe would be captured in the molten glass and very little could be released into the environment(V. M. Fthenakis, 2005). Releases to the aquatic environment could potentially occur after decommissioning only if such modules are disposed of in unlined landfills without leachate collection and treatment systems and assuming that the cadmium compounds leach out. However, cadmium telluride is encapsulated between two sheets of glass and is unlikely to leach to the environment under normal conditions.

By the material movement pattern, there are three basic types of migration of heavy metals from CdTe PV cell projects: mechanical, physicochemical and biological migration. Mechanical migration refers to heavy metal ions being mechanically transported by water currents in the dissolved or particulate form. The migration process is in line with hydraulics principles. Physicochemical migration refers to the migration and transformation process of heavy metals in the form of simple ions, complex ions or soluble molecules through a series of physical and chemical actions (hydrolysis, oxidation, reduction, precipitation, dissolving, complexation, chelation, adsorption, etc.) in the environment. This is the most important migration and transformation pattern of heavy metals in the aquatic environment. The migration and transformation result decides the presence, enrichment status and potential ecological risks of heavy metals in the aquatic environment. Biological migration refers to migration of heavy metals through metabolism, growth and death of organisms. This complicated migration process is a combination of physical chemistry and biology. All heavy metals can migrate through organisms. Consequently, heavy metals are enriched in some organisms and constitute a hazard to humans through amplification of the food chain.

Adsorption of colloid is a major way for heavy metals in water to transform into the solid phase. Adsorption of colloid has a significant impact on process transformation of heavy metals in the aquatic environment and biological and ecological effects. With high surface area, surface energy and charge, colloid can strongly adsorb various molecules and ions and thus has a significant impact on the migration of heavy metal ions in water bodies. In natural water bodies, only an extremely low amount of cadmium telluride and its associated heavy metal products is dissolved, mainly enriched in the solid phase.

1.2 Analysis of CdTe PV cell dispersion pattern in ambient air

The reference case of atmospheric cadmium emissions during lifecycle of CdTe PV modules are shown in Table 4 in Paper One. The results in the table reflect the allocation of Cd emissions during mining, smelting and refining to Cd (0.58 percent allocation) as well as Zn production (remainder of allocation).

Table 4 in Paper One shows that the reference estimate of total air emissions is 0.02 g Cd/GWh of electricity produced (Fthenakis, 2004),. The main contributor to Cd air emission in the later assessment was PV utilization, under the assumption of Cd loss during fires. As discussed earlier, extensive experimental tests proved that Cd emissions are limited by capture in molten glass during fires. Also, the assessment uses more recent data for determining emissions during mining, smelting/refining, and decommissioning of end-of-life products.

During the PV power plant construction and operation phases, CdTe solar cells are durable and do not produce any emissions during extreme conditions of accelerated aging in thermal cycles from +80 to 80°C. Every PV generation, regardless of technology, is a zero-emissions process. The thin CdTe/CdS layers are encapsulated between sheets of glass or plastic. Unless the module is ground to a fine dust, dust particles cannot be generated. The melting point of CdTe is 1,041°C, and evaporation starts at 1,050°C. Sublimation occurs at lower temperatures, but the vapor pressure of CdTe at 800°C is only 2.5 torr (0.003 atm). The melting point of CdS is 1,750°C and its vapor pressure due to sublimation is only 0.1 torr at 800°C. Therefore, it is impossible for any vapors or dust to be emitted when using PV modules under normal operating conditions.

The two leading methods of making CdTe thin films- electro-deposition and vapor transport -- use cadmium very efficiently. About 1% is wasted in the former process, and about 10-30% in the latter. In both processes, the cadmium is collected and is safely disposed of or recycled. The controlled (with HEPA filters) vapor emissions into the atmosphere amount to 3 g of Cd per ton of Cd used (Fthenakis, 2004).

CdTe PV cells will not generate cadmium emissions into the air throughout their use and recycling. PV modules have an expected lifecycle of 25-30 years and will not emit cadmium emissions into the air when they are normally used since the semiconductor material is sealed between two glass panes with an industriallaminate . Atmospheric emissions during/ after decommissioning will be zero. Even if pieces of modules inadvertently make it to a municipal waste incinerator, cadmium will dissolve in the molten glass and would become part of the solid waste (Marco Raugei, 2012).

Pollutants in the atmosphere are transported, mixed and diluted under the impact of the horizontal movement of air, turbulent diffusion and atmospheric disturbances of varying scales.

Wind and turbulence are the most direct and essential factor that determines the state of diffusion of pollutants in the atmosphere and the determinant of pollutant dispersion. Weather conditions that are conducive to increasing wind speed and enhancing turbulence are all conducive to dilution and diffusion of pollutants. Otherwise, the pollution will become worse.

Wind’s impact on diffusion of pollutants has two dimensions: overall transport and dilution. Wind direction determines the direction of pollutant migration, while wind speed determines the speed of pollutant migration. Pollutants are always transported from the windward side to the leeward side. The leeward side of the pollution source has to face heavier pollution compared to the windward side. So it’s necessary to know local wind direction to decide the ambient pollution in an area. Plus, the higher the wind speed is, the more air containing pollutants is cleaned in a unit time, the better the dilution effect is. In general, the concentration of pollutants in the atmosphere is proportional to the total emissions of pollutants, and is inversely proportional to wind speed.

In addition to overall horizontal movement, the atmosphere has secondary movements of varying scales that are different from the direction of main flow, also known as vortex flow. Such extremely irregular atmospheric movement is called atmospheric turbulence. Atmospheric turbulence is related to atmospheric thermodynamic factors -- atmospheric vertical stability, near-surface wind speed, underlying surface and other mechanical factors. The turbulence resulting from the former is called thermal turbulence, while that resulting from the latter is called mechanical turbulence. Atmospheric turbulence is the combined result of the above two types of turbulences. Atmospheric turbulence is most represented by near-surface atmosphere conditions. Alternating high and low wind speed and swaying wind direction are concrete manifestation of atmospheric turbulence. Atmospheric turbulence leads to intensive mixing of various parts in the turbulence field. When pollutants are emitted into the atmosphere, the highly concentrated pollutants are constantly mixed with clean air and irregularly dispersed towards other directions due to turbulent mixing. As a result, pollutants are continuously diluted.

Pollutants dispersed in the atmosphere then enter soil and water bodies through dry and wet deposition and follow the pollutant dispersion patterns thereof. As further discussed in section 3.1, the atmospheric dispersion of worst-case emissions from a CdTe PV array fire have been modeled by Beckmann and Mennenga (2011), with ground-level Cd concentrations estimated to be below health screening levels in the surrounding environment.

1.3 Analysis of CdTe PV cell migration pattern in soil

In the lifecycle of cadmium telluride, cadmium enters soil directly only in (1) mining of zinc and lead ores and (2) smelting and refining of zinc and lead and indirectly through ambient air and water in other processes.

There are many forms of cadmium in soil. But there are generally two categories: water-soluble and non-water-soluble cadmium. Ionic and complex state water-soluble cadmium represented by $CdCl_2$, Cd $(WO_3)_2$ can be absorbed by crops and thus pose high risks for living creatures. Insoluble cadmium compounds such as CdS, $CdCO_3$, falling under the category of non-water-soluble cadmium, are hard to migrate and be absorbed by plants. The two categories are mutually convertible under certain conditions.

The migration and transformation of cadmium in soil is greatly influenced by the activity of hydrogen ions (pH) and the activity of electrons (Eh). When the soil is acidic, the solubility of cadmium is high; conversely, when the soil is alkaline, the solubility of cadmium is low. Studies show that, pH and exchangeable calcium in soil are negatively correlated to the content of cadmium in rice.

Sonoda et al. in Japan studied cadmium adsorption by soil Eh. Under oxidizing conditions (500mV), when soil and cadmium containing solution interact, over 20% of adsorbed cadmium is exchangeable. When phosphate is added, exchangeable cadmium decreases, while insoluble cadmium increases. But available cadmium reaches up to 45%. When soil is in reducing conditions (200mV), the addition of phosphate can further reduce exchangeable cadmium and increase insoluble cadmium, because reducing conditions are conducive to the formation of insoluble cadmium phosphate. Especially when Eh drops to 0mV, no matter whether phosphoric acid is applied or not, insoluble cadmium in soil will increase anyway. It will lead to the formation of not only phosphate, but also more stable cadmium sulfide. Mizuno et al. in Japan believe that rice's absorption of Cd from soil is closely related Eh. Insoluble cadmium CdS on one hand is subject to redox reaction:

$$CdS \rightleftharpoons \rightleftharpoons Cd^{2+}+S^{2-},\ S^{2-}-2^{e} \rightleftharpoons \rightleftharpoons S\downarrow$$

leading to increased concentration of available Cd^{2+}; on the other hand, sulfur ions are oxidized into sulfuric acid, leading to decreased soil pH and increased CdS solubility.

Study on cadmium-polluted soil shows that the content of Cd is related to that of Zn, Pb and etc. to some extent. Where the content of cadmium is high, the content of Zn, Pb and Cu is high as well. The presence of zinc can inhibit the absorption of cadmium in plants. Therefore, in addition to the impact of soil pH and Eh, the migration and transformation of cadmium is subject to the impact of accompanying ions, such as Zn^{2+},Pb^{2+},Fe^{2+},Cu^{2+}, Mn^{2+}, Ca^{2+}, PO^{3-} and etc. When the content of available Cd^{2+} in soil is high, there's a good chance that the content of cadmium in rice is also high.

Due to topsoil's adsorption and chemical fixation of cadmium, cadmium in soil is usually concentrated within several centimeters from the soil surface. Meanwhile, in soil, cadmium delivers minimum pollution capacity, which is an important feature of cadmium pollution in soil. Therefore, a slight increase in the cadmium content in soil can drive up the content of cadmium in rice accordingly. For this, a stringent environmental standard has been put in place to control soil cadmium pollution, no more than 1.0ppm, to be specific.

2 CdTe PV cells' cumulative environmental impact assessment

2.1 Analysis of CdTe PV cells' cumulative impact on water

The analysis of cumulative environmental impact of CdTe PV cell projects shall take cumulative impact of other related projects in the past, present and foreseeable future into consideration.

The CdTe life cycle assessment (LCA) analysis shows that (1) mining of zinc, lead, and copper ores, (2) smelting/refining of zinc, lead, and copper, (3) purification of Cd and Te, (4) production of CdTe, (5) manufacture of CdTe PV modules, and, (6) disposal of end-of-life modules, all have an impact on the aquatic environment.

CdTe thin-film solar cell projects will not bring heavy metal pollution in water bodies during construction and operation. Surface water and groundwater contamination may occur to some extent during the early mining and smelting phases. As stated earlier, Table 4 in Paper One reflects the allocation of Cd emissions during mining, smelting and refining to Cd (0.58 percent allocation) as well as Zn production (remainder of allocation).

Relevant studies and First Solar data show that module manufacturing and recycling of end-of-life modules can bring residual levels of cadmium pollution to water after on-site wastewater treatment (1.3 mg Cd/m^2 of module; Raugei and Fthenakis 2010). Addressing sewage generated during CdTe solar cell module manufacturing, diversion by type, treatment by nature and individual monitoring shall be adopted. After being subject to physical or chemical action, some cadmium into water bodies remain in water bodies, some are enriched in bottom mud, and some enter the food chain after being absorbed by aquatic plants and animals and thus pose potential health risks to humans, animals and plants. Residual levels of cadmium in treated wastewater from module manufacturing and recycling are in accordance with regulatory discharge limits. See further discussion in section 4.1 and Table 8.

2.2 Analysis of CdTe PV cells' cumulative impact on air

The CdTe LCA analysis shows that (1) mining of zinc, lead, and copper ores, (2) cadmium and tellurium from zinc, lead, and copper smelting/refining, (3) cadmium and tellurium purification, (4) CdTe production, (5) CdTe module manufacturing and (6) disposal of end-of-life modules all have an impact on the ambient air.

CdTe thin-film solar cell projects will not increase heavy metal pollution to the environment during the normal installation and operation phases, but can bring cadmium pollution to the atmosphere to some extent in the early phases including mining, ore grinding, roasting, smelting and refining. Relevant studies and First Solar data show that cadmium pollution to the atmospheric environment can be generated during solar PV module manufacturing, thin-film production and laser engraving. Cadmium-containing exhaust from the processes is generally disposed of in a compliant manner after dust collection . The remaining residual cadmium-containing pollutants in exhaust after dust collection are recirculated within the manufacturing facility with average factory-wide Cd concentrations in indoor air ($<0.2\ \mu g/m^3$) that are well below occupational exposure limits ($5\ \mu g/m^3$).

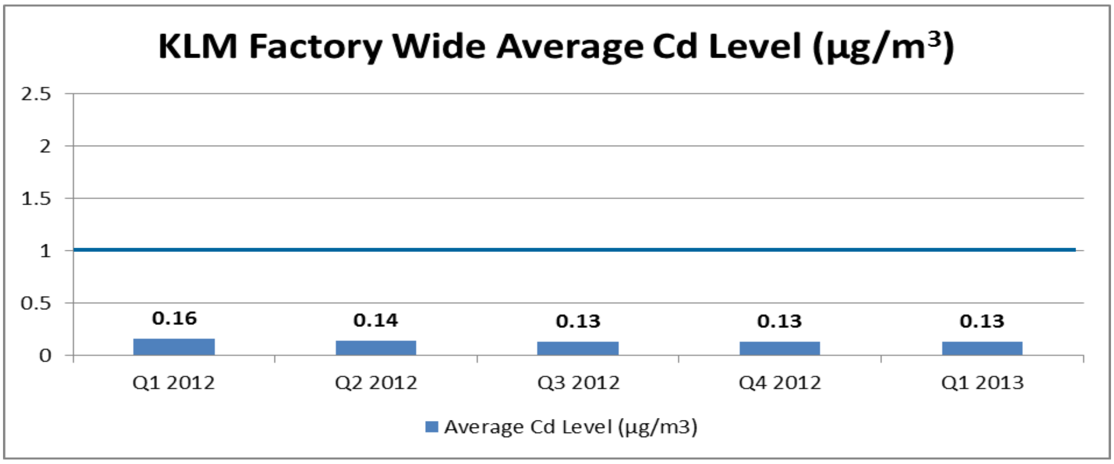
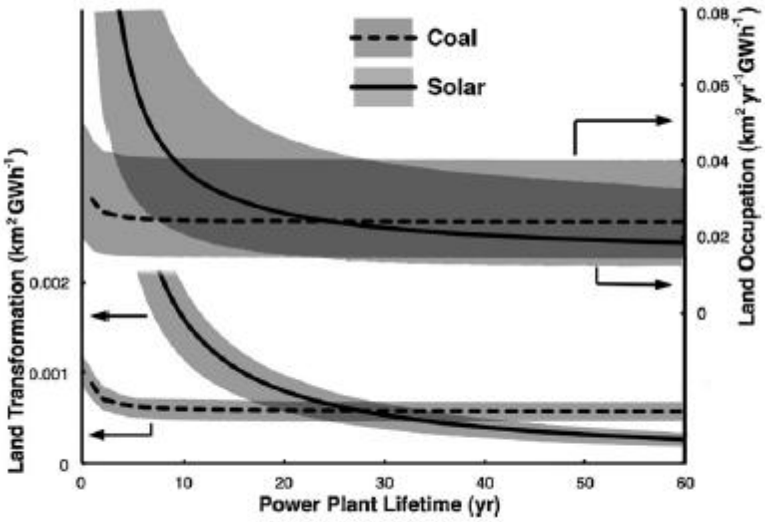


Figure 1. KLM factory wide average Cd level

2.3 Analysis of CdTe PV cells' cumulative impact on land

Cadmium telluride has an impact on land throughout the six processes of LCA. However, since only the module use process is studied according to First Solar data, the present document provides cumulative impact analysis of the said process only. So do the following chapters.

According to the study of Turney and Fthenakis (2011), land transformation and land occupation throughout the lifecycle during the operation phase are calculated as shown in Figure 2.



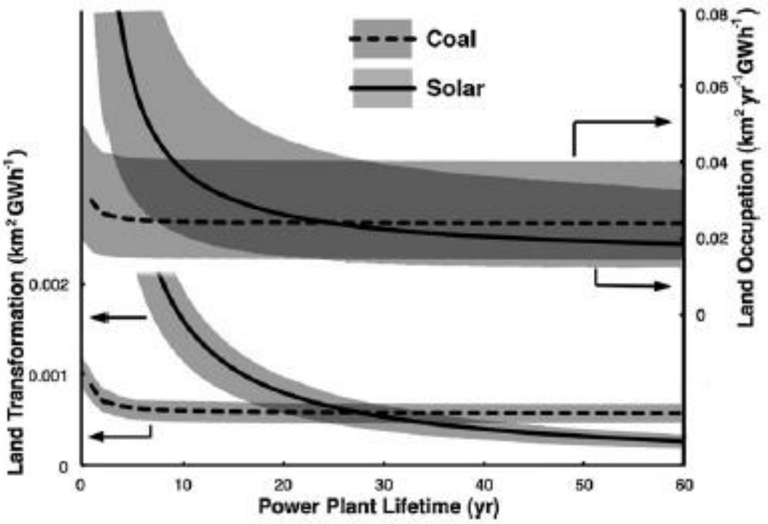


Figure 2 Comparisons of land use intensity metrics for large-scale solar and coal power.

The results for land transformation show parity between solar and coal at 26 years, whereas those for land occupation show parity at 24 years. The latter is a more informed metric since it includes information about the recycling times of land following disturbance. A 30-year old photovoltaic plant is seen to occupy15% less land than a coal power plant of the same age per GWh generated. As the age of the power plant increases, the land use intensity of photovoltaic power becomes significantly smaller than that for coal power. The sensitivity in the calculations, as dependent on input parameters, is shown by the shaded belts in Fig. 2. Land transformation per plant capacity $km^2\ GW^{-1}{}_{ac}$ show parity between solar and coal after 30years, with a range from 27 to 40 years (data not plotted).

2.4 Analysis of CdTe PV cells' cumulative impact on ecology

The study of Turney and Fthenakis (2011) shows that solar power plants have a certain impact on wildlife and habitat.

The majority impact to wildlife and habitat is due to land occupation by the power plant itself. The power plant is typically enclosed by a fence. Hiding spots, preying strategy, food availability will all be affected. Power plants can also prevent growth of vegetation or keep free of vegetation. In either case, a significant alteration to the vegetation occurs. The PV panels themselves will cast shadows and change the microclimate, causing an unstudied effect on vegetation.

McCrary et al. measured death of birds, bats, and insects at the Solar One concentrating solar power tower near Daggett, California, USA in desert land. Six birds per year died and hundreds of insects per hour were incinerated in the intense light. This impact was concluded to be low compared to other anthropogenic sources of bird and insect fatality. The environmental impact statement for the solar power tower Ivanpah Solar Electric Generating System, California, USA reported that “significant impact” would occur for the threatened desert tortoise, five special-status animal species, and five special-status plants in the local area. An environmental impact report prepared for the 550MWp Topaz photovoltaic project located in grasslands and abandoned farmlands of central California, USA found the potential for significant impact to dozens of protected animal and plant species in the region. For both projects, extensive mitigation programs were implemented to reduce the impacts to acceptable levels.

The impact to wildlife will be tightly correlated to the biodiversity of the land on which the power plant is built. Sunlight and water availability can significantly alter the biodiversity in any of these biomes, by a factor of two, and endangered species can live in any biome. Consequently, a customized study of the wildlife and ecosystem surrounding each power plant is recommended as a best practice. For example, see U.S. project environmental impact reports in References. In addition, power plants’ impact on biological corridors is obvious.

In addition to potential impacts on biodiversity, solar projects can have potential benefits for biodiversity due to their static use of land. Although construction projects always involve disturbance of existing flora and fauna, with solar parks there is a chance to improve the quality of habitats for various plant and animal species and even to create new habitats (T. Peschel, 2010).Table 1 summarizes ecological impacts of solar power plants displacing power generated by the traditional U.S. technologies.

Table 1 Impacts to wildlife and habitat of solar energy relative to traditional U.S. power generation (Turney and Fthenakis, 2011).

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 power 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	Eliminates 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	Reduce change	Beneficial	High	Solar emits ~ 25× less greenhouse gases

2.5 Analysis of CdTe PV cells' cumulative impact on climate change

The study of Turney and Fthenakis (2011) shows that, solar power plants have a positive impact on climate change due to reduced emissions of carbon dioxide compared to traditional power generation.

Given~72GWh km^{-2} yr^{-1} as time-averaged generation for the solar power plant, emissions of CO_2 from the remainder of the lifecycle of solar power are 16-40 g CO_2 kWh^{-1} for 1,700 $kWhm^{-2}$ yr^{-1}insolation. The net emission results in Table 2 shows that solar power is still a very low carbon alternative to traditional U.S. power generation.

Table 2 Emissions of CO_2 from the lifecycle of large-scale solar power.

Carbon dioxide emissions (g CO_2 kWh^{-1})		
	Best case	Worst case
Loss of forest sequestration	+0.0	+8.6

Respiration of soil biomass	+0.0	+1.9
Oxidation of cut biomass	+0.0	+35.8
Other phases of the lifecycle	+16.0	+40.0
Total emissions of solar	+16.0	+86.3
Fossil fuel emissions avoidance	-850.0	-650.0
Total including avoidance	-834.0	-563.7

Methane and nitrous oxide are also important greenhouse gases released by coal power plants. For comparison, the radioactive forcing of CO_2, methane, and nitrous oxide, respectively, is 1.7, 0.5, and 0.2Wm^{-2}, and fossil fuel combustion contributes 73%, 27%, and 8% of the respective amounts. Emissions of CH_4 and NO_2 from the lifecycle of solar power in forests are likely to be much lower than from fossil fuels, suggesting another GHG benefit for switching electricity generation from fossil to solar power.

Land use affects local climate, microclimate, and surface temperatures, e.g., urban heat islands exist near metropolitan areas. Solar panels have low reflectivity and convert a large fraction of insolation into heat, which leads to concern that they may affect global or local climate. Nemet investigated the effect on global climate due to albedo change from widespread installation of solar panels and found the effect to be small compared to benefits from the accompanying reduction in greenhouse gas emissions. Nemet did not consider local climates or microclimates though they have been recently evaluated by Fthenakis and Yu (2013) who observed prompt dissipation of thermal energy with distance from alarge solar farm and complete cooling of the solar array at night.

Table 3 lists the climate change impacts from solar energy in forested regions. The presence of the forest affects most of the impacts, particularly the CO2 emissions. Field research is needed to establish the effect of the power plant on local climate and micro-climates.

Table 3 Impacts to climate change from solar power, relative to traditional U.S. power generation (Turney and Fthenakis, 2011).

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	Reduces GHG	Beneficial	High	Strong benefit

emissions	emissions			
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

2.6 Analysis of CdTe PV cells' cumulative impact on the social environment

The study of Turney and Fthenakis (2011) shows that solar power plants have both positive and negative impact on the social environment.

Table 4 lists the impacts to human health and well-being from solar energy in forested regions. Most of the impacts are beneficial, due to a reduction in toxic emissions arising from the combustion of fossil fuels. For example, a recent study found that 49% of lakes and reservoirs in the U.S. contain fish with concentrations of mercury (Hg) above safe consumption limits. Solar power equipment releases 50-1,000 times less direct Hg emissions than traditional electricity generation, i.e., ~0.1gHgGWh^{-1} as compared to ~15gHgGWh^{-1} from coal. In the US, at least 65% of the mercury deposited in lakes and reservoirs originates from burning fossil fuels. Photovoltaics made with CdTe emit ~0.02 g Cd GWh^{-1} when manufactured with clean electricity, which is 100-300 times smaller than emissions from coal power generation. Emissions of NO_x, SO_2, and many other pollutants, are orders of magnitude smaller than those from traditional power. Emissions of these toxics and others, including particulates, are significant burdens on human health. Carbon dioxide emissions also pose risks to human health and well-being, due to climate change and the associated effects: sea level rise, extreme weather, food security, and socioeconomic change. Fossil fuel power plants emit a large proportion of greenhouse gases worldwide, and much of the remaining emissions are due to petroleum use that can be partly replaced by electricity from clean power sources.

Impacts on aesthetics and recreational opportunities from solar power are less clear. Recent proposed legislation introduced in California attempted to place large tracts of land out-of-bounds for solar energy plants, partly due to recreational and visual impacts, and partly for ecological concerns (Woody, 2009). The visual and recreational impacts are difficult to quantify but much progress has been made by the U.S. Forest Service over the past decades toward appraising visual resources during land development. A similar approach could be used for recreational resources. Regarding recreational resources, note that a switch to solar power would decrease mercury deposition on lakes and rivers, thereby improving their utility for fishing and recreation. Mountaintop mining could also be reduced or displaced by deployment of large-scale solar power, thereby opening vast amounts of highland forest to recreational opportunity.

Table 4 Impacts to human health and well-being relative to traditional U.S. power generation (Turney and Fthenakis, 2011).

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Emissions of mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~ 30× less
Emissions of cadmium	Reduces emissions	Beneficial	High	Solar emits ~ 150× less
Emissions of other toxics	Reduces emissions	Beneficial	Moderate	Solar emits much less
Emissions of particulates	Reduces emissions	Beneficial	High	Solar emits much less
Other impacts				
Noise	Reduces noise	Beneficial	Low	Less mining noise; less train noise
Recreational resources	Reduces pollution	Beneficial	Moderate	Cleaner air; cleaner fishing
Visual aesthetics	Similar to fossils	Neutral	Moderate	Solar farms vs. open pit mines
Climate change	Reduces change	Beneficial	High	Solar emits ~ 25× less g h g
Land occupation	Similar to fossils	Neutral	Moderate	See Section 4.1. of Turney and Fthenakis (2011)

3 Environmental risk assessment

3.1 Environmental risk assessment

Since the U.S. have a proven track record in installation and operation of CdTe PV power plants, for example, in California and Arizona, and a similar project has been introduced to Ordos, Inner Mongolia in 2010, it does make sense to refer to EIS or ESA documents in the U.S. In these documents, environmental risks are summarized in two aspects: (i) disaster risks incurred from various disasters (due to natural, human factors), e.g. geological disasters, earthquakes, floods and fires; and (ii) health risks incurred from exposure to pollution or hazardous substances. Particular attention is given to biological resources including flora and fauna and environmentally sensitive locations such as schools and hospitals.

Based on the review of available literature and the comparison of EIA documents on CdTe PV power plants in China and other countries, lifecycle analysis is conducted. The emphasis is put on environmental risk assessment for the CdTe cell production, PV power plants installation and operation, and decommissioning and disposal phases, which is summarized as follows.

(1) Manufacture of CdTe module

The processes from purchase of raw materials to manufacture of modules are all carried out in a closed workshop. Generated atmospheric pollutants generally enter the ventilation system of the workshop equipped with highly efficient HEPA (High Efficiency Particulate Air) filters. The efficiency of HEPA filters in collecting particulates of mean diameter of 0.3um is 99.97%. Cleaning wastewater from all workshop sections all flow to the in-house sewage treatment plant for centralized treatment. In this way, wastewater and air emissions generated at the site are effectively controlled. So, environment risks from the manufacture process mainly lie in substances and equipments of concern and resulting credible incidents such as equipment start/stop, maintenance, environmental equipment failure and fires.

i. Identify risk sources

Substances and equipments of concern are covered herein. Substances of concern mainly include toxic, hazardous, inflammable and explosive substances. Glass carrier cleaning related acids and alkalis and other harmful substances during manufacture of CdTe modules all fall under the category. As trade secrets are involved, only concentrated sulfuric acid, sodium hydroxide and etc. are identified for the present. Specifics will be given in the project EIA phase.

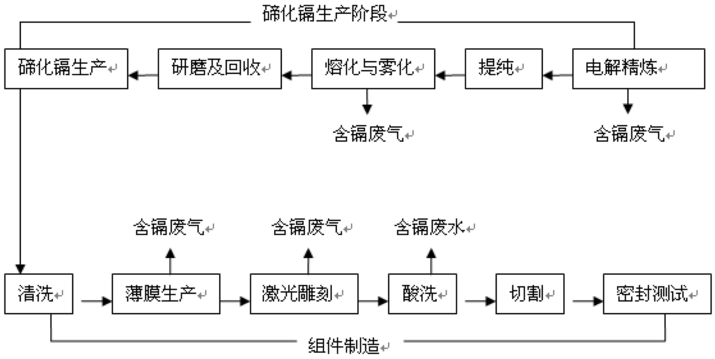


Figure 3 Manufacture process of CdTe solar modules

Currently available information shows that major substances of concern during manufacture of modules include concentrated sulfuric acid and sodium hydroxide. The specific scale of risk and whether they shall be classified as major risk sources need to be further determined based on the use and storage volume. According to the manufacturing process of CdTe solar modules, manufacturing equipments available in the workshop sections of semiconductor deposition, cell definition, and module finishingare where cadmium containing equipment exhaust and waste water are generated.

ii. Identify environmental risk-related credible incidents

Environmental risk-related credible incidents during manufacture of CdTe solar modules include equipment maintenance, start/stop, incidental sewage efflux at sewage treatment facilities, environmental equipment failure, fires, and etc.

With regards to incidental sewage efflux at sewage treatment facilities, production and cleaning wastewater are all transported into the in-house wastewater treatment system, treated on a batch basis and discharged after the applicable wastewater discharge standards are met. (the Chinese version still retains this sentence) Therefore, sewage treatment facilities shall have sufficient capacity. It's advisable to conduct online monitoring of heavy metals (Cd), acidity (pH) and chemical oxygen demand (COD) in water pollutants and develop contingency plans. For example, treated wastewater in First Solar manufacturing and recycling facilities is held in batch discharge tanks and tested before being confirmed for discharge.

HEPA filter failure may lead to inadvertent cadmium particulate emissions within the manufacturing facility. However, since CdTe can hardly exist in the gaseous state at normal temperature, pressure, once the vacuum or high temperature environment is damaged, CdTe vapor will condense rapidly into solid particles clinging to the cavity or pipe wall and thus hardly diffuse in the gaseous state to pose health risks to human beings. Specific risk mitigation measures include guaranteed filter replacement frequency, automated filter efficiency monitoring systems, effective job and settlement records, training in the use and inspection of filters and etc.

(2) PV power plant installation and operation

Environmental risks from PV power plant installation and operation are summarized as follows:

i. Improper use, storage and disposal of petroleum products could lead to emissions into the aquatic or terrestrial environment, which, when going beyond a certain dose, can pose potential threat to human health. Such risks can occur in the underlying construction and operation phases. The specifics are as follows:

a. The underlying construction phase: Risk-induced behaviors may include installation of site channels, excavation of wells and establishment of a temporary storage tank, site grading and removal of surface vegetation, development of drainage control systems, underground structures and outdoor switching stations, deployment of transmission lines, laying of solar photovoltaic panels, deployment of fire prevention systems and etc.

By means of strict control and management of hazardous substances and timely removal of oil spills, the occurrence of sudden disasters and release of harmful substances during the construction phase are usually short-term and can be controlled within the construction site, and the risk level thereof is acceptable.

b. The operation and maintenance phases of the power plant: Risk-induced behaviors may include daily transportation of petroleum products as used in vehicles, and use and improper disposal of hazardous substances, hydraulic fluids, and herbicides. Along with the operation of the project, hazardous substances including lubricants, and waste oils adsorbents can also be generated.

c. The decommissioning phase of powerplants: Containment measures in the power plant decommissioning phase are necessary to limit the release of petroleum substances.

ii. Risks related to activation of pollutants in soil or groundwater to increase exposure of humans or wildlife and pose health hazards when the exposure level exceeds the threshold.

a. The underlying construction phase: Risk-induced behaviors include disturbance of the soil environment at the site that was once a contaminated site or agricultural sewage irrigation area in the underlying construction phase, which may become a new source of pollution and increase the amount of exposure of onsite staff.

b. The operation and maintenance phase: The disturbance to soil and underground water in this phase is smaller than that in the underlying construction phase. The replacement of panels, substation equipment and digital surveillance systems within a small framework may bring some environmental risks to staff exposed to hazardous substances.

c. The decommissioning phase: This phase may cause pollution disturbance of soil and groundwater. Related behaviors include removal of solar panels and brackets, underground facilities at least 2 feet deep, buildings, and power transmission poles and conductors, and closing and abandoning wells and underground oil tanks. Once leakage of hazardous substances is identified, it’s necessary to remove impacted soil and dispose of responsibly.

iii. Risks related to workers that are exposed to pollutants or the concentration of hazardous substances is excessive and goes beyond the OSHA allowable amount; or result in the public’s direct and indirect contact and thus increased exposure.

In the three phases of underlying construction, operation and decommissioning, the exposure of workers to hazardous substances is temporary. Workers shall operate in strict accordance with OSHA requirements, which, however, cannot avoid the risk of incidents. So it’s necessary to develop and follow *Contingency Plans for Environmental Risks*.

iv. Risks related to the increase in the exposure amount of residents of the land on which the power plant is built, or to causing significant damage, injury or death;

a. The underlying construction phase: risk-induced behaviors may include engineering activities and use of equipment, which can lead to loss, increased risk of injury, and even death as a result of electric shock and wildland fires. Fires are related to cigarette lighter, refueling and driving, etc.

b. The operation and maintenance phase: The occurrence probability of risk during operation is related to arc and line sparks. Environmental risks can be mitigated by taking measures such as deployment of baffle walls and fire systems and enclosing of electronic equipments.

v. Fires

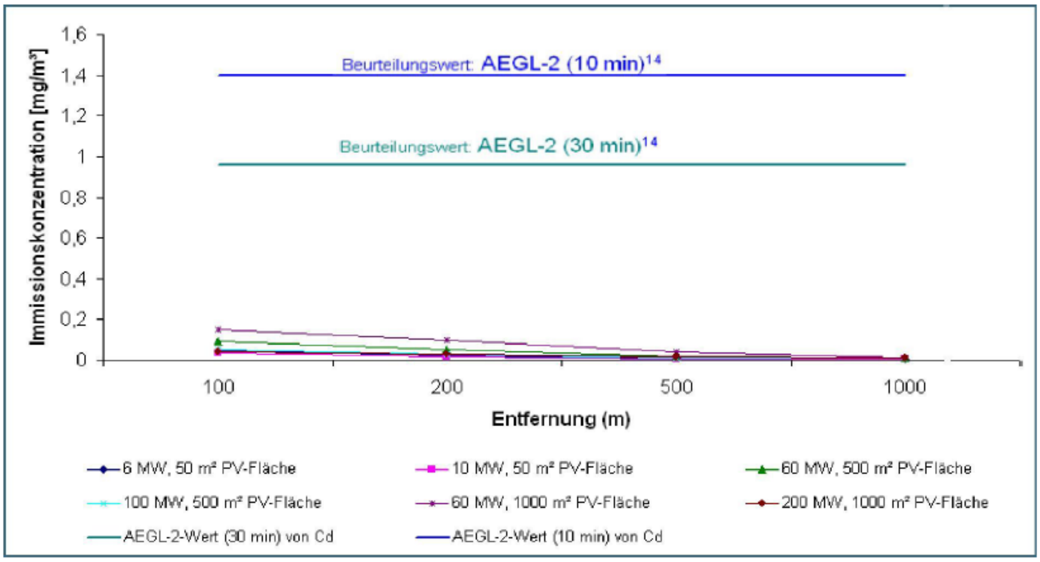
CdTe thin-film cells, the central part of solar modules, are located between two sheets of glass. Such modules contain the semiconductor CdTe consisting of the compound of heavy metal Cd and non-metallic Te. In China, CdTe has been included in the Hazardous Wastes Catalogue. But regarding solar thin-film modules, requirements are not clearly defined yet. Due to its presence, the heavy metal Cd is deemed a key target under the environmental risk assessment.

Vasilis M. Fthenakis analyzed routine releases and potential accidental releases of cadmium compounds in PV cells in *Lifecycle impact analysis of cadmium in CdTe PV production* released in 2003, concluding that it's impossible for any vapors or dust to be emitted when using PV modules under normal conditions and CdTe releases are unlikely to occur during accidental breakage. The only scenario of potential exposure is if a fire consumes the PV module and releases cadmium from the material into the air.

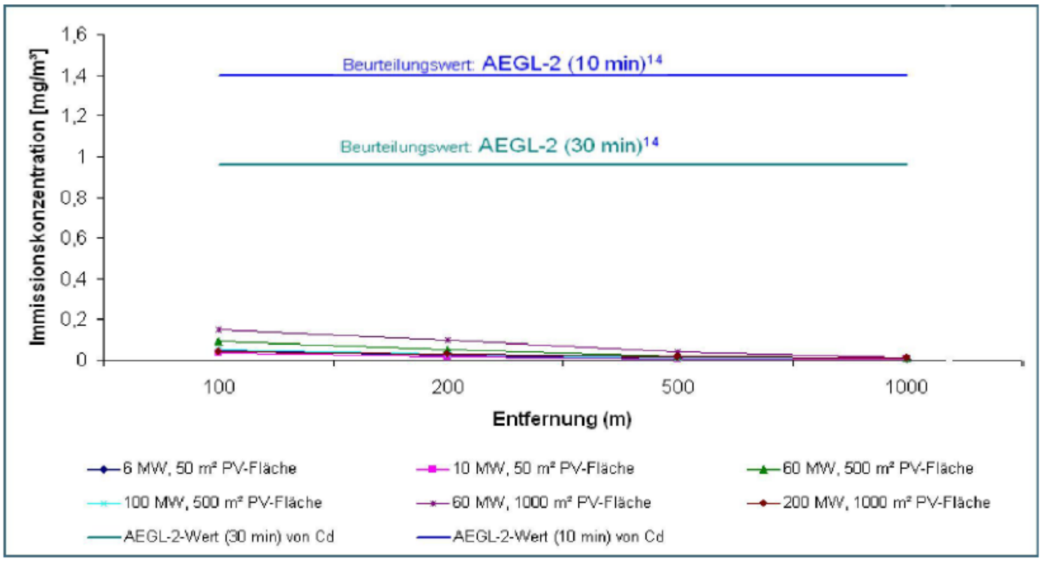
In fully developed house fires, flame temperatures can reach 800-1,000°C. In industrial fires where other fuels are present, higher flame temperatures could occur. Steinberger conducted thermogravimetric analyses of pure CdTe and reported that the material, exposed to air, remains stable until about 1,050°C, whereas it started to evaporate at around 900°C under non-oxidizing conditions (lack of air). But it shall be noted that oxidizing conditions are the only realistic ones for high temperature tests, since lack of oxygen would extinguish the fire. Some studies show that when the flame temperature reaches above 700°C, the glass will melt and wrap around the CdTe thin-film before solidifying. So 99.96% of Cd will be retained in glass. Plus, in previous studies, samples were cut from the center of standard modules. But in the real word, a cm-wide blank area without cadmium is reserved on the four sides of conventional modules. The design is aimed at preventing edge leakage. Cd needs to diffuse 1cm to reach the opening of the edge, so the actual leakage probability may be even lower than that shown in Fthenakis' study.

In general, the release of CdTe from conventional CdTe modules encapsulated in glass pieces in fires is low and negligible.

It is worth noting that in Worst-case Fire Dispersion Modeling (assuming total release of Cd) the accidental release model is used for calculation(Beckmann and Mennenga 2011). Assuming roof-top Cd emission source strength 50 m^2, 500 m^2, and 1000 $m^2$to be respectively mapped to 14-66 g Cd/m^2, ground-level Cd concentrations [mg Cd/m^3]depending on the distance (from 100m to 10,000 m) from the fire site are estimated. The mapping relation is as shown in the figure below. According to the acute exposure guideline levels (AEGL) for Cd and safety threshold 4 mg/m^3 for CdO, within a certain distance, the ground-level Cd concentrations are estimated to be below environmental screening levels in the surrounding environment.



Depiction of cadmium emission concentrations depending on the distance from the fire site with average cadmium contents of 14.0 g/m^2 (Case 1).



Depiction of cadmium emission concentrations depending on the distance from the fire site with average cadmium contents of 14.0 g/m^2 (Case 1).

Figure 4 Ground-level Cd concentration depending on the distance [mg Cd/m³]

Mitigation measures: As with any large structure or building, it’s necessary to develop strict *Emergency Plans for Fire Incidents* and make drills, and set up health protection distance based on the actual need in project-specific environmental impact assessment to ensure the safety of sensitive points in the surrounding environment of the project. Plus, necessary measures, e.g. protective equipments and clothings, shall be taken before proceeding to firefighting.

vii. Damaged PV modules

In the early construction period of the project, the damage of individual panels can hardly be avoided when PV solar panels are installed. Plus, damage and leaching risks can potentially occur during waste treatment of solar panels after decommissioning of the power plant.

Under normal circumstances, when modules are damaged in dry or neutral aqueous environment, cadmium leaching to the surrounding environment is negligible. But in acid rain environment, Cd emissions shall be highlighted. In China, erosion and dissolution of acid rain in some regions may lead to leaching of cadmium from modules. So it's advisable to perform independent leaching test for modules in the case. Note that the presence of acid alone is not sufficient to cause leaching. For example, the recycling process requires crushing modules to mm-scale pieces and agitating in acid to recover semiconductor materials. Module breakage rate is below 1% over 25 years (0.04%/yr), over one-third of which occurs during shipping and installation. In addition, routine inspections and power output monitoring diagnose broken modules for takeback and recycling. Most module breakage is limited to small fractures rather than shattering due to the lamination of the two sheets of glass, which limits potential exposure area.

(3) Decommissioning

PV deployment is beginning to globalize beyond the EU into emerging markets, where end-of-life collection and recycling is voluntary and landfill is currently the predominant form of waste disposal. As PV solar panels under condition of damage and acidic leaching may generate cadmium ions, there are potential environmental risks and health risks to residents living besides landfills. This is a top concern in other countries along with the development of CdTe PV cells, but relevant research hasn't been conducted in China yet.

Releases to the aquatic environment could occur after decommissioning only if such modules end up in unlined landfills, the semiconductor materials leach out, and there is no leachate collection and treatment system. However, cadmium telluride is encapsulated between two sheets of glass which are laminated and is unlikely to leach to the environment under normal conditions. But there are risks in acid conditions. An independent leaching toxicity test of the modules shall be performed prior to disposing of modules to landfill.

Vasilis M. Fthenakis (2004) concluded that the environmental risks from CdTe PV are minimal. The estimated atmospheric emissions of 0.02 g of Cd per GWh of electricity produced during all the phases of the modules' life, are extremely low. Large-scale use of CdTe PV modules does not present any risks to health and the environment, and recycling the modules at the end of their useful life completely resolves any environmental concerns.

Recycling of waste solar panels is the best way to minimize the environmental risks thereof and conserve resources. And it's also feasible for the present to submit to qualified organizations for disposal at landfills.

3.2Emergency response and remedial measures in case of incidents

1) Enable well-regulated storage, use and disposal of hazardous substances.

Where hazardous substances are involved, a responsibility owner shall be delegated. H*azardous Substances Regulations* shall be developed and put in place for strict management of their use. Hazardous wastes, e.g. shall be submitted to qualified organizations for disposal.

2) Establish fire and accident pools and take measures to guarantee effective drainage and prevent flooding

(i) set up fire and accident pools near the solar panel quarter to prevent fires; (ii) based on the site terrain, build drainage and water conservancy facilities, e.g. regional drains, flood intercepting trenches, etc., to address sudden flooding; and (iii) develop *Fire Prevention Measure for the Construction and Operation Phases* and *Flood Prevention Measure for the Construction and Operation Phases* and put them in place.

3) Develop *Contingency Plans for Incidents and Environmental Risks*

The Contingency Plans shall be developed in strict compliance with the *Guidance on Preparing Emergency Rescue Plans for Hazardous Chemicals Incidents* to cover (i) hazardous targets, available safety, fire and personal protective equipments and tools in the vicinity and their distribution; (ii) emergency rescue organizations, personnel and responsibilities; (iii) alarm and communications; (iv) disposal measures after occurrence of incidents; (v) staff evacuation; (vi) danger zone isolation; (vii) detection, rescue, relief and control measures; (viii) treatment of the injured; (ix) site protection and decontamination; (x) emergency rescue guarantee; (xi)triggers for graded emergency response; (xii) emergency rescue termination procedures; (xiii) emergency response training programs; and (xiv) drill programs.

4) Develop other plans and preventive measures, including, SWPP (Stormwater Pollution Prevention Plan), SPCC (Spill Prevention Control and Countermeasure Plan) and HSP (Health and Safety Plans).

5) Highlight recycling of solar panels and eliminate arbitrary abandonment. Introduce *Solar Cell Recycling*, *Solid Waste Recycling*, etc.

3.3 Human health risk assessment

(1) Eco-toxicity of Cd and CdTe

Cd is a relatively rare element in the earth's crust. Elemental cadmium is a silver white or lead gray metal, with a density of 8.642 g/cm^3, melting point of 321 °C, and boiling point of 765 °C (Table 1). Environmental issues incurred by cadmium exposure, including cadmium ecotoxicology, migration and transformation in flora and fauna, ecological issues as a result of bioaccumulation and biomagnification, and tissue damage, endocrine disorders, cardiovascular diseases, reproductive dysfunction and cancer triggered by accumulation in human body, have become a common concern. The Itai-itai disease found in Japan, a well documented public nuisance, is caused by cadmium poisoning.

In contrast, little is known about CdTe's toxicological profile and regulatory agencies usually apply cadmium (Cd) criteria as a best approximation. However, due to relative stabilization and low solubility, CdTe may have different toxicological properties. Joseph Zayed and Suzanne Philippe studied acute oral and inhalation toxicities in rats with cadmium telluride. This study showed that the median lethal concentration of CdTe is 2.71 mg/L/4 hours while its median lethal oral dose was considered to be greater than 2,000 mg/kg. According to cadmium toxicity data of The Registry of Toxic Effects of Chemical Substances data bank, for 4 hours of exposure, this concentration leads to a value of 0.0031 mg/L/4 hours, which is very much lower than the value for CdTe (2.71 mg/L/4 hours). For aquatic organisms, S. Kaczmar (2011) studied CdTe's acute aquatic toxicity to zebra fish and concluded that CdTe is not toxic (fatal or indirectly fatal) to fish under water saturation.

(2) Human health risk practices and assessment

From PV power plant operation to module decommissioning under the project, it's not likely to emit any vapor or dust when PV modules are used under normal conditions. In general, it's believed that CdTe will not have adverse effects on human body until CdTe containing dust is ingested and inhaled or improperly disposed of (e.g. improper use of gloves). Therefore, in the U.S., potential risks to human body from disposal of end-of-life modules at landfills are highlighted. Regarding health risks from the manufacturing process, emphasis is put on occupational safety and health evaluation.

Parikhit Sinhaet. al. performed fate and transport analysis to evaluate potential exposures to cadmium (Cd) from cadmium telluride (CdTe) photovoltaics (PV) for rainwater leaching from broken modules in a commercial building scenario.In this highly conservative study, where all the CdTe content of the broken modules was assumed to be released to the environment, results showed that exposure point concentrations in soil, air, and groundwater are one to six orders of magnitude below conservative (residential soil, residential air, drinking water) human health screening levels. Potential exposures to Cd from rainwater leaching of broken modules in a commercial building scenario are highly unlikely to pose a potential health risk to on-site workers or off-site residents.

Swiatoslav Kaczmar evaluated the potential for human health and ecological impacts from disposal of CdTe photovoltaics in non-sanitary landfills. The evaluation considered potential human health and ecological impacts from waste disposal to an unlined landfill under acidic conditions. With respect to human health impacts, estimated cancer risks were well below the screening limit (1.0×10^{-6}) for both landfill conditions. Likewise, chronic non-cancer hazard indices (HI) for both acidic and basic landfill conditions are well below the screening limit (1), indicating that the land-filling of CdTe PV modules would not be expected to result inreleases of Cd to groundwater or surface pathways at levels representing potential health impacts.

(3) Occupational safety and health assessment

Due to high concentration and long-time of Cd exposure during manufacture of CdTe PV solar modules, the impact on human health shall be highlighted. It's necessary to perform occupational safety and health assessment. During the operation phase and after decommissioning, along with declining exposure, occupational safety and health risks drop as well. For human health risk assessment, urine cadmium levels are primarily indicative of long term cadmium exposure, blood cadmium levels are primarily indicative of recent exposure, and β-2 microglobulin levels are a secondary indicator.

i. Cadmium exposure

The CdTe module manufacturing process will inevitably bring exposure to cadmium containing dust. Related processes and environmental monitoring data of the Kulim module manufacturing facility in Malaysia show that there are no module processing steps that result in worker exposure at or above $5\mu g/M^3$ for an 8-hour time weighted average which is the OSHA (US Occupational and Health Administration) PEL (permissible exposure limit) for cadmium. The only manufacturing activity in excess of the OSHA PEL is maintenance to the semiconductor deposition equipment and spraying of $CdCl_2$. Addressing this, First Solar adopts High Efficiency ParticulateAir (HEPA) filters to protect from cadmium dust. Plus, equipment maintenance and cleaning workers must wear appropriate protection such as protective clothing for risk prevention.

ii. Employee health test results

Over the past decade, First Solar has accumulated much data on biological test results of its workers. The tests are carried out by a third party. John R. Bohland and Ken Smigielski documented over 700 medical monitoring tests on workers from First Solar, Ohio in the U.S., to track any biological responses to occupational cadmium exposures. A total of 44 samples were acquired. The facility, put into operation for 10 years, has the longest operating duration of any First Solar manufacturing facility. The test results showed compliant blood cadmium and urine cadmium results.

Take the Kulim facility in Malaysia as an example. Malaysia OSHPELs for blood and urine cadmium concentration are 5μg/L and 3μg/g respectively. In 2007-2012, the Kulim facility has carried out blood and urine cadmium concentration monitoring of over 1,000 workers for six consecutive years and concluded that the values stay far below OSHA PELs. The statistical data for 2011 and 2012 are still being processed.

The semiconductor deposition equipment maintenance and $CdCl_2$ spaying and baking processes pose higher risks. Amongst these workers, maintenance staff are subject to a blood and urine cadmium test every six months, while staff exposed to $CdCl_2$were subject to the test annually prior to 2012 and once every three years beginning2012. Test results showed that staff engaged in the two processes are still in a safe working environment.

iii. Risk mitigation measures

First Solar is trying to mitigate health risks from the manufacturing processes in the following ways: (i) strengthen environmental monitoring in different workshops to ensure compliant cadmium exposure concentration; (ii) request workers to wear protective clothing and respiratory protection equipped with HEPA filter cartridges when engaged in equipment maintenance and cleaning; (iii) keep close monitoring of workers' health checks and increase the monitor frequency for high-risk processes, e.g. organize a blood and urine cadmium test for semiconductor deposition equipment maintenance staff every six months; (iv) conduct on-the-job employee training and increase risk prevention awareness; and (v) develop contingency plans and perform regular drills.

4CdTe cell lifecycle CP assessment

4.1 CdTe cell lifecycle CP assessment

(1) CP indicators in EIA

The selection of indicators shall be conducted in light of the principle of being systematic, independent and pragmatic. Cleaner production (CP) indicators in EIA include manufacturing process and equipment requirements, resource and energy utilization indicators, product indicators, pollutant emission indicators (prior to end treatment), waste recycling indicators, etc. Manufacturing process and equipment indicators and product indicators are qualitative indicators, while the others are quantitative indicators.

Throughout the lifecycle of CdTe PV cells, cleaner production is mainly embodied in mining and smelting of lead and zinc ores, synthesis of CdTe and disposal of waste solar panels. The reference indicators for the three phases are as shown in the table below.

Table 5 Reference indicators by phase throughout the lifecycle of CdTe PV solar modules

Lifecycle	Indicator	Content	Remark
Lead and zinc ore mining and smelting	Manufacturing process and equipment requirements	Sophistication of manufacturing processes and equipments	Refer to *Cleaner Production Assessment Indicators for the Lead and Zinc Industry (Trial)*
	Resource and energy utilization indicators	Resource utilization rate, water consumption rate, water recycling rate, energy consumption rate (coal power, etc.)	
	Pollutant generation indicators (prior to end treatment)	Tons of COD, SO_2 and Cd generation	
Synthesis of CdTe PV modules	Manufacturing process and equipment requirements	Sophistication of manufacturing processes and equipments	Compare to other solar panel industries
	Resource and energy utilization indicators	Water consumption rate, water recycling rate, energy consumption rate (coal power, etc.)	
	Pollutant generation indicators (prior to end treatment)	Tons of COD, SO_2 and Cd generation	
	Cadmium recycling indicator	Cadmium recycling indicator	
Disposal of waste PV panels	Waste recycling indicator	Waste PV panel recycling rate; if pollutants are recycles, then water resources, energy consumption rate and metal cadmium	It's advisable to submit to qualified organizations for centralized disposal or recycling

		recycling rate shall be considered	

(2) Lifecycle based cleaner production and pollutant emissions

i. Overview of existing literature resources on energy use

Parikhit Sinha, Amy Meader, et al. (2013) in their study of lifecycle water usage in CdTe photovoltaics summarized energy and resource consumption per unit.

Table 6 Key life cycle inventory (LCI) parameters during CdTe production

Lifecycle Phase	Parameter	Value	Unit per m^2 module	Sample Size
Module (weighted average across U.S., German, and Malaysian facilities)	Electricity	29.7	kwh	3
	Solar Glass	8.39	kg	3
	Glass Tempering	8.39	kg	3
	Flat Glass	8.15	kg	3
	Tap water (from utility bills)	182.8	kg	3
BOS (from Topaz Solar Farm, California)	Steel, low-alloyed	10.2	kg	3
	Zinc coating	0.63	m2	3
	Tap water [5]	89.1	kg	3
	Inverter, 500kW	0.00022	-	3
	Copper	0.88	kg	3
Takeback and Recycling (from U.S. facility)	Electricity	4.38	kwh	3
	Hydrogen peroxide, 50% in water	0.57	kg	3
	Transport, van < 3.5 tonne	1.62	t-km	3
	Transport, lorry > 16 tonne	8.67	t-km	3
	Water deionized (from instrument readings)	5.42	kg	3

Table 7 Direct and total lifecycle water withdrawal (L/MWH) for CdTe PV

Lifecycle Phase	Direct (on-site)	Total
Module	31	224
BOS[a]	15	106-150
Takeback and Recycling	1	51
Total	47	382-425

Calculated based on the above table, the water withdrawal throughout the lifecycle of CdTe photovoltaics stays at around 382-485L/Mwh. The statistical data in LCI of CdTe cells show that direct energy and water consumption per m^2 PV module in the lifecycle is 34 kWh and 277 L respectively.

ii. Pollutant emissions in First Solar practices

Take the Kulim facility in Malaysia as an example. Pollutant emissions per m^2 during the manufacturing process are as shown in Table 8. Given the sharp fluctuations, the indicators are only used for analogy reference for cleaner production indicators.

Table 8 Pollutant emissions during the manufacture of PV modules

Final Discharge Parameters	**Regulatory Final Discharge Limit**	**Waste stream from manufacturing/others (min-max)**	**KLM1 WWTP Actual Final Discharge (min-max)**	**KLM2 WWTP Actual Final Discharge (min-max)**	**KLM3/4 WWTP Actual Final Discharge (min-max)**	**KLM5/6 WWTP Actual Final Discharge (min-max)**
pH	**5.5-9**	1 - 10	6.6- 7.6	6.9- 7.6	6.9- 7.6	7.0- 7.7
COD (mg/L)	**200**	90 - 450	1 - 64	1 - 47	0 - 20	1 - 54
Cadmium (mg/L)	**0.02**	15- 80	0- 0.005	0- 0.005	0- 0.005	0.005-0.010
Iron (mg/L)	**5.0**	10 - 20	0 - 2	0- 0.09	0- 0.16	0- 0.15

4.2 Aggregate indicators suggestions

According to the *Twelfth Five-Year Plan for Environmental Protection in China*, the country exerts control and management on the total emissions of the four major pollutants of COD, SO2, NH3-N and NOX. So it’s advisable to adopt the combined emissions of the above four conventional pollutants as a pollution emission indicator.

Also, in the *Twelfth Five-Year Plan for Heavy Metal Pollution Integrated Control (2011)*, the control over total heavy metal emissions is introduced for the first time, and the five heavy metals including mercury, chromium, cadmium, lead and arsenic are defined as the key targets subject to monitoring and pollutant emission control. The Plan divides the country into two categories: priority areas, including 14 major provinces such as Inner Mongolia, Hunan, Guangxi and Qinghai and 138 key protection zones, and non-priority areas. So it's advisable to adopt the total emissions of the heavy metal cadmium as another pollutant emission indicator.

5. Environmental measures and suggestions for CdTe PV cell projects

5.1Mitigation measures for reduced impact on water

In the mining phase, heavy metal wastewater mainly consists of underground drainage, leaching wastewater from waste rock piles, production water for mining and underground water gushing in mines. Mitigation measures for the mining phase and the rest of the life cycle include: (i) set up centralized collection tanks for recycling or effluence after treatment, adopt cutting-edge ore selection and mining technologies, and minimize underground water gushing to reduce the impact on surface water and groundwater; (ii) decide on appropriate sites featuring good solar resources, low population density and sufficient land area for construction and operation of CdTe solar power plants; (iii) carry out wastewater recycling in a stringent manner to minimize wastewater effluence during production of CdTe powder and manufacture of PV modules; (iv) prevent leaching at landfills in the decommissioning phase and deploy leachate collection and treatment systems; (v) develop sound project management plans and emergency response plans, and adopt lifecycle management and pollutant control technologies; and (vi) develop well-designed training mechanisms and responsibility matrixes and put them in place.

5.2Mitigation measures for reduced impact on air

In the mining phase, exhaust pollutants include underground ventilation exhaust from underground blasting, drilling, loading and unloading and dust. Mitigation measures are as follows: (i) reduce dust by spraying water and minimize dust's impact on workers by requesting them to wear personal protection; (ii) enable regular water sprayingon waste rock dumps and ore yards for dust suppression since open ore yards and motor transport can generate dust, and partition using and timely soil reclamation of waste rock dumps to minimize dust's impact on the air; (iii) adopt cutting-edge gas recycling and treatment and reuse technologies and ensure workers' safety protection in the smelting and refining process; (iv) develop sound project management plans and emergency response plans, and adopt lifecycle management and pollutant control technologies; and (v) develop well-designed training mechanisms and responsibility matrixes and put them in place.

During PV project construction, site sprinkling with water several times a day can effectively control dust. Reduced vehicle travel speed can also make a difference. Dust can also come from building material stacking in open air and mixing operations. Minimizing such operations on windy days and reducing building material stacking in open air is an effective way to control such dust.

5.3Mitigation measures for reduced impact on land

CdTe LCA pollutant emission phase analysis shows that the phases including (1) mining of zinc, lead, and copper ores, (2) Cd and Te as byproducts of smelting/refining of zinc, lead, and copper, (3) purification of Cd and Te, (4) production of CdTe, (5) manufacture of CdTe PV modules, and, (6) disposal of end-of-life modules can all have environmental impacts on land use.

To improve land utilization and reduce CdTe solar cell projects' impact on land, it's advisable to take the following measures: (i) reduce land use in the mining phase and minimize underground mining; (ii) reduce land use in other phases.

Regarding the mining phase, the project's impact on land mainly includes temporary land occupation in the construction phase and permanent land occupation upon project completion. For land damaged due to temporary land occupation in the construction phase, it's advisable to backfill the mined-out area with waste rocks, cover with topsoil, and then make the land smooth and compact during the mine closure period. After mine closure, all on-site production and living facilities shall be removed. The temporary waste rock dumps shall be covered with soil and leveled for ecological restoration.

During PV project construction, for disturbed ground within the site, coverage by gravel and use of soil stabilizers can be adopted to protect disturbed bare ground and minimize soil erosion. To prevent new soil erosion as a result of wind erosion of temporary mounds and sand and gravel dumps, simple protection around such mounds can be enabled. Steel plates can be placed around the mounds for wind blocking and anti-dust nets used to cover temporary mounds within the site on windy days. The surface of such mounds can be sprinkled with water to prevent wind erosion. Excavation needs to be backfilled promptly and the amount of mounds minimized. Upon completion of construction, temporary buildings should be removed and construction waste should be transported for disposal in accordance with the sanitation authority.

5.4Mitigation measures for reduced impact on ecology

CdTe LCA pollutant emission phase analysis shows that of (1) mining of zinc, lead, and copper ores, (2) Cd and Te as byproducts of zinc, lead, and copper smelting/refining (3) purification of Cd and Te, (4) production of CdTe, (5) manufacture of CdTe PV modules, and, (6) disposal of end-of-life modules, (1) and (5) have a greater impact on the ecology.

In the mining phase, minimize temporary land occupation and damage to vegetation. In the reclamation phase, perform topsoil backfill in an orderly manner so that the precious surface humus on the plateau can be effectively preserved and utilized, increase the success rate of vegetation recycling, and strengthen the tending of reclaimed sites.

In the operation phase, (i) strictly prohibit treading on vegetation and soil and avoid human activities' adverse impact on vegetation and soil; (ii) increase workers' environmental awareness; and (iii) strictly prohibit hunting of wild animals.

The protection and restoration from the project's ecological impact shall be performed in the order of "avoidance→reduction→compensation" to minimize human activities' damage to natural resources and the ecological environment and thus meet the goal of "a balance between development and preservation".

6 Environmental supervision and management during production and project implementation

6.1 Environmental supervision and management during production

To ensure effective operation of the environmental management system during the project's production and operation process, it's necessary to develop environmental management programs, which shall cover:

(1) To put applicable national and local environmental guidelines, policies and laws and regulations in place, organize environmental education and technical training, improve employees' environmental awareness and technical levels, and enable increased responsibility for pollution control;

(2) To develop long-term environmental protection plans and annual pollution control plans and put them in place, regularly check the operational status of

environmental facilities and equipment maintenance and management, and strictly control emissions of waste water, waste gases and solid wastes;

(3) To stay informed of internal pollutant emissions status and develop internal environmental reports accordingly;

(4) To effectively balance and control environmental funds and make payment for excessive emissions;

(5) To assist line authorities in putting the policy of “environmental facilities must be designed, deployed and put into operation along with major works” in place, and participate in the validation and final acceptance of environmental programs;

(6) To organize environmental monitoring, check the company’s environmental status and report environmental monitoring information to line authorities in a timely manner;

(7) To investigate and handle internal pollution incidents and disputes, organize experiments and researches on waste treatment and use technologies, and develop classified and graded filing and handling systems of pollution incidents;

(8) To develop a companywide EMS (Environmental Management System) to enable compliance with ISO14000; and

(9) To develop cleaner production audit plans in light of the principle of “Prevention First” to achieve combined environmental and economic benefits.

Note that First Solar manufacturing and recycling facilities have obtained ISO9001, ISO14001 and OHSAS18001 certificates.

6.2 Environmental supervision and management during project implementation

Throughout project construction, local authorities of environmental protection, water conservancy, transportation and sanitation constitute the central part of environmental monitoring during project construction, while in a specific or sensitive process, banking, auditing, judiciary and media organizations are also an integral part of the monitoring system.

(1) The contract entered into between and by the project owner and contractor shall cover provisions of environmental protection during project construction, including ecological protection (water and soil conservation), environmental pollution control, pollutant emissions management, environmental education for construction workers and rewards and penalties thereof.

(2) The contractor shall increase environmental awareness, strengthen

environmental management of living quarters and construction sites, develop reasonable schedules, enable rigorous planning and civilized construction, put all environmental measures in place, implement and operate environmental facilities along with major works at the same time, earmark environmental funds, and avoid poor quality and delay.

(3) The contractor shall pay special attention to soil and water conservation during project construction, protect soil and vegetation along the project area as far as possible.

(4) For construction sites, living quarters and other temporary construction facilities, strengthen environmental management and avoid fugitive emissions of sewage from construction, which shall be transported to designated locations if possible. At sites with heavy dust, dust suppression measures shall be taken. Upon completion of project construction, the contractor shall clean up and restore construction sites in a timely manner and properly dispose of living waste and ballast from construction to reduce dust. Construction sites shall be in compliance with the *Emission standard of environment noise for boundary of construction site (GB12523-2011)*.

(5) Take compensatory measures seriously, conduct construction supervision and inspection of environmental facilities properly, guarantee the quality of environmental facilities, and put the policy of “environmental facilities must be designed, deployed and put into operation along with major works” in place.

7Consistency analysis of CdTe PV project

7.1 Consistency with existing policies and regulations

In the Encouraged Catalogue of Encouraged Foreign Investment Industries in The *Catalogue for the Guidance of Foreign Investment Industries (2007 Revision)*, (18) under 21 “Communications equipments, computers and other electronic equipments manufacturing” of III “Manufacturing” defines “Manufacture of hi-tech green batteries: nickel-hydrogen batteries, nickel-zinc batteries, silver zinc batteries, lithium-ion batteries, high-capacity wholly sealed maintenance-proof lead-acid batteries, solar cells, fuel cells and cylindrical zinc-air batteries. "

February 2013, the *Catalogue for the Guidance on Adjustment of Industrial Structure* (2011 Version) (Revised)

I Encouraged

5. New Energy (1) solar thermal power systems, solar photovoltaic power generation system integration technology development and application, inverter control system development and manufacturing

19. Light industry (18) various advanced solar photovoltaic cells and high purity crystalline silicon (conversion efficiency of monocrystalline silicon solar cells > 17%, polycrystalline silicon cells > 16%, silicon-based thin-film cells > 7%, CdTe cells > 9%, copper indium gallium selenide cell > 12%).

According to Liu Xiangxin (2013), the U.S. and EU both hold a positive attitude towards the CdTe PV industry, but have environmental regulation of cadmium compounds. The U.S. Brookhaven National Laboratory and Department of Energy have applied to list CdTe into the National Toxicology Program (NTP) as a subject of human long-term exposure research to collect objective data. The EU has restrictions on electronic products containing cadmium, requiring that the cadmium content in materials shall not be greater than 0.01% (i.e. 100 ppm) though PV has been excluded from the scope of the RoHS restriction.

The EU WEEE Directive, that came into effect in August 2005 and was recently revised, requests manufacturers of EEE products to ensure takeback and recycling of waste EEE products in scope. Photovoltaic panels are included in the scope of the recast WEEE Directive, requiring producers as of 2014 to fulfill the collection and recovery regulations in the 27 EU Member States.

Due to its low cost of manufacturing, relatively high efficiency and energy yield, and environmental attributes including successful recycling strategies, First Solar's CdTe solar panels have been widely recognized in major EU markets represented by Germany. The development of a third party based recycling mechanism has now become a regulatory prerequisite for all PVPV module manufacturers to access the market under the recast WEEE Directive (European Union, 2012, Directive 2012/19/EU).

In June 2010, the European Regulators excluded photovoltaic modules from the scope of the RoHS Directive, and separated the scope of RoHS from the scope of WEEE.Beginning in 2014, PV modules will be included in the scope of the EU WEEE Directive.(the deleted sentence is retained in the revised Chinese version.)

The EU's cadmium management policies are exemplary to other countries and regions and have led to the introduction of similar policies in China, South Korea, Japan and California. China, for example, has now exerted the same restrictions on cadmium containing products as RoHS in the EU by introducing the *Administrative Catalogue for the Control of Pollution Caused by Electronic Information Products*. Products containing hazardous elements will be included in the catalogue if alternatives thereto are already technically and financially feasible. Products in the catalogue are not allowed to enter the market until they are certified by China Compulsory Certification. Products not included in the catalogue or export and military products are not subject to the restrictions. The most recent Catalogue has not included photovoltaic products containing CdTe and CdS. But CdTe has already been listed in the *Catalogue* *of Toxic Chemicals Severely Restricted on the Import and Export in China (2012)*. Regarding its import and export, an application must be filed to the Ministry of Environmental Protection of the P.R.C.

Table 9 The *Catalogue of Toxic Chemicals Severely Restricted on the Import and Export in China (2012)*

S/N	Chemical	Alias	Customs Product Number	Unit
65	CdTe		2842902000	Kg

In summary, China encourages solar power and solar cells, but as in the EU and U.S. imposes restrictions on the use of the toxic heavy metal cadmium. It lists CdTe in the *Catalogue of Toxic Chemicals Severely Restricted on the Import and Export in China.*

7.2 Attainment of increased public awareness

In recent years, China has witnessed some environmental group events, from the maglev project in Shanghai to the PX project in Xiamen, and from the molybdenum-copper project in Shifang to the sewage discharge project in Qidong, featuring increasing participants, scope and impact. These events are all related to environmental protection, particularly EIA.

In these environmental group events, the public rely on reasonable and lawful approaches to protect their own interests and influence an individual project and even environmental decision-making at higher levels. The growing power of the public, as the principal part of the society and a bottom-up power compared to the government, on the one hand is a manifestation of social democracy and progress, and on the other hand is thought-provoking.

China has been valuing information disclosure and public participation. The release of *Regulation of the People's Republic of China on the Disclosure of Government Information* and *Measures for the Disclosure of Environmental Information (Trial)* in May 2008 was conducive to the public’s right to access environmental information, supervise and participate in. The *Interim Measures for Public Participation in the Environmental Impact Assessment* released in March 2006 announced public participation in EIA and defined the procedures, contents and ways of public participation. This is the first and the only of its kind in China to address public participation in administrative approval so far. The introduction of *Measures for the Disclosure of Environmental Information (Trial)* and *Interim Measures for Public Participation in the Environmental Impact Assessment* represents a major breakthrough in information disclosure and public participation in the field of administrative approval in China.

The introduction of public participation in EIA can help (i) guarantee the public's right to access environmental information, supervise and participate in, increase the public's environmental awareness, accelerate the tackling of environmental issues in China, and identify new ways to environmental protection; (ii) increase the public's part in environmental decision-making, promote democratic decision-making, reduce decision-making risks, and enable more scientific decision-making; and (iii) build a platform where the government and the public interact so that decision-makers can get access to public opinion in a timely manner, alleviate social conflicts and promote social harmony and progress.

EIA has been legalized in all developed countries and some Asian countries. Public participation is a part of it. For specific projects, Article 6 in *Interim Measures for Public Participation in the Environmental Impact Assessment* states that "for a project that requires public opinion, the environmental impact statement without public input shall not be accepted by the administrative department of environmental protection."

The introduction of public participation in a specific project can help properly guide the public and take the initiative. The early consideration of adverse impact on the environment and society is the key to successful implementation and operation of a project.

In the CdTe PV project as with large-scale construction projects in general, a variety of approaches including expert evaluation, seminars and media campaigns can be leveraged to help the public gain insights into the project's environmental impact and thus accept the project. The specifics are as follows:

(1) Organize expert argumentation to get scientific and fair conclusions;

(2) Disclose project information in an active and timely manner, e.g. perform two announcements as required in the EIA phase, and post annual environmental reports at the company website in the operation phase;

(3) Organize hearings or seminars to enable the public's access to project information and thus eliminate the public's concerns. Invite the public to visit the plant in the operation phase if necessary;

(4) Respond to the public's questions in a timely manner; and

(5) Collect inputs from the public in the phases of project proposal, feasibility study and EIA in light of the principles of openness and visibility.

7.3 Attainment of existing standards

Currently available standards in China that are related to cadmium emissions and acceptable concentration: *Integrated emission standard of air pollutants* (GB16297-1996), *Quality standard for ground water* (GB/T14848-93), *Environmental quality standards for surface water* (GB3838-2002), *Integrated* *wastewater discharge standard* (GB8978-1996), *Environmental quality standard for soils* (GB 15618-1995) and etc.

Table 10Aquatic environment standards by level

	Designation	I	II	III	IV	V
Quality standard for ground water(GB/T14848-93)	Cadmium (mg/L)	≤0.0001	≤0.001	≤0.01	≤0.01	>0.01
Environmental quality standards for surface water(GB3838-2002)	Cadmium (mg/L)	≤0.001	≤0.005	≤0.005	≤0.005	≤0.01
Integrated wastewater discharge standard(GB8978-1996)	Total cadmium (mg/L)	Maximum acceptable concentration≤0.1				

Table 11 *Integrated emission standard of air pollutants*

S/N	Pollutant	Maximum acceptable emission concentration (mg/m^3)	Maximum acceptable emission rate (kg/h)			Monitoring concentration threshold of fugitive emission	
			Emission pipe (m)	L2	L3	Monitoring point	Concentration (mg/m^3)
11	Cadmium and its compounds	0.85	15 20 30 40 50 60 70 80	0.050 0.090 0.29 0.50 0.77 1.1 1.5 2.1	0.080 0.13 0.44 0.77 1.2 1.7 2.3 3.2	Maximum concentration beyond border	0.040

Table 12 Environmental quality standard for soils

Level	L1	L2			L3
Soil pH	Natural background	<6.5	6.5-7.5	>7.5	>6.5
Cadmium (mg/kg) ≤	0.20	0.30	0.60	1.0	

In the U.S., there isn't a uniform water use classification standard available. When the nationwide water quality assessment is conducted, eight water uses are considered pursuant to Section 305(b) "Water Quality Assessment" of the federal *Clean Water Act*. There are four stream water uses. In the biennial nationwide river water quality assessment, the states evaluate stream segments for attainment of those uses and report to EPA for summary.

On the basis of stream water use attainment assessment, there are three other water quality indicators that can help further identify water impairment: major, moderate and minor stressors. The environmental standards for water in China and the U.S. are significantly different. The standards system in the U.S. is more flexible, which is in line with Chinese standards in general.

Malaysia has relatively strict environmental standards, setting the cadmium emissions limit to 0.02mg/L, compared to 0.1 mg/L in China.

Moreover, according to the *National Catalogue of Hazard Waste* (Order No. 1, 2008, of the Ministry of Environmental Protection (MEP) and the National Development and Reform Commission (NDRC)):

Article 4 Solid and liquid wastes that are not included in this Catalogue or the *Catalogue for Classification of Medical Wastes* and identified, according to the national standards and methods to identify hazardous wastes and by experts who are organized by the competent environmental protection department under the State Council, to possess hazardous properties and thus belong to hazardous waste shall be added to this Catalogue at a proper timing.

Article 5 The nature of the compound of hazardous waste and non-hazardous waste shall be determined in accordance with the national standard for identifying hazardous wastes.

There's no way to determine whether CdTe solar cell wastes are hazardous wastes based on FS data only. So it's advisable to conduct identification for extraction toxicity as soon as possible.

7.4 Suggestions

(1) To identify whether a CdTe solar panel is hazardous waste pursuant to the *Identification standards for hazardous wastes -- Identification for extraction toxicity* (GB 5085.3-2007) as soon as possible. If a CdTe solar panel is identified as hazardous waste, it can be recycled or disposed of pursuant to the *Standard on the Pollution Control in Landfill Hazardous Waste* (GB 18598-2001).

(2) To develop CdTe related emissions standards. Given that there aren't CdTe emission standards available in China yet and cadmium is a toxic heavy metal, it's necessary to introduce one as soon as possible to ensure the safety during its use and production. Note that in the absence of CdTe-specific emission standards, Cd standards have been conservatively applied.

(3) Given that First Solar has had a CdTe thin-film installed base up to 7Gw in

the US, EU and Japan and that the plants installed have been operating reliably, it is advisable for China to install a test CdTe thin-film PV system with moderate capacity at a secure and controllable site for runtime and environment impact assessment, to provide reliable inputs for decision-making.

(4) According to the *Twelfth Five-Year Plan for Environmental Protection*, China will conduct planned management of total emissions of the four major pollutants including COD, SO_2, NH_3-N and NO_X. So it's advisable to calculate the emissions of the above four conventional pollutants per m^2 solar panel as the pollutant emission indicator.

(5) Also, in the *Twelfth Five-Year Plan for Heavy Metal Pollution Integrated Control (2011)*, the control over total heavy metal emissions is introduced for the first time, and the five heavy metals including mercury, chromium, cadmium, lead and arsenic are defined as the key targets subject to monitoring and pollutant emission control. The Plan divides the country into two categories: priority areas, including 14 major provinces such as Inner Mongolia, Hunan, Guangxi and Qinghai and 138 key protection zones, and non-priority areas. So it's advisable to regard cadmium as a special pollutant and calculate cadmium emissions per m^2 solar panel. For the layout of the CdTe solar cell industry, it's necessary to take local conditions into consideration, keep in line with ecological function zoning, avoid the ecological red line, and select areas with potentials and high environmental capacity for the project site.

(6) To ensure workers' personal protection, set reasonable working hours and job rotation systems, and define reasonable safety distances.

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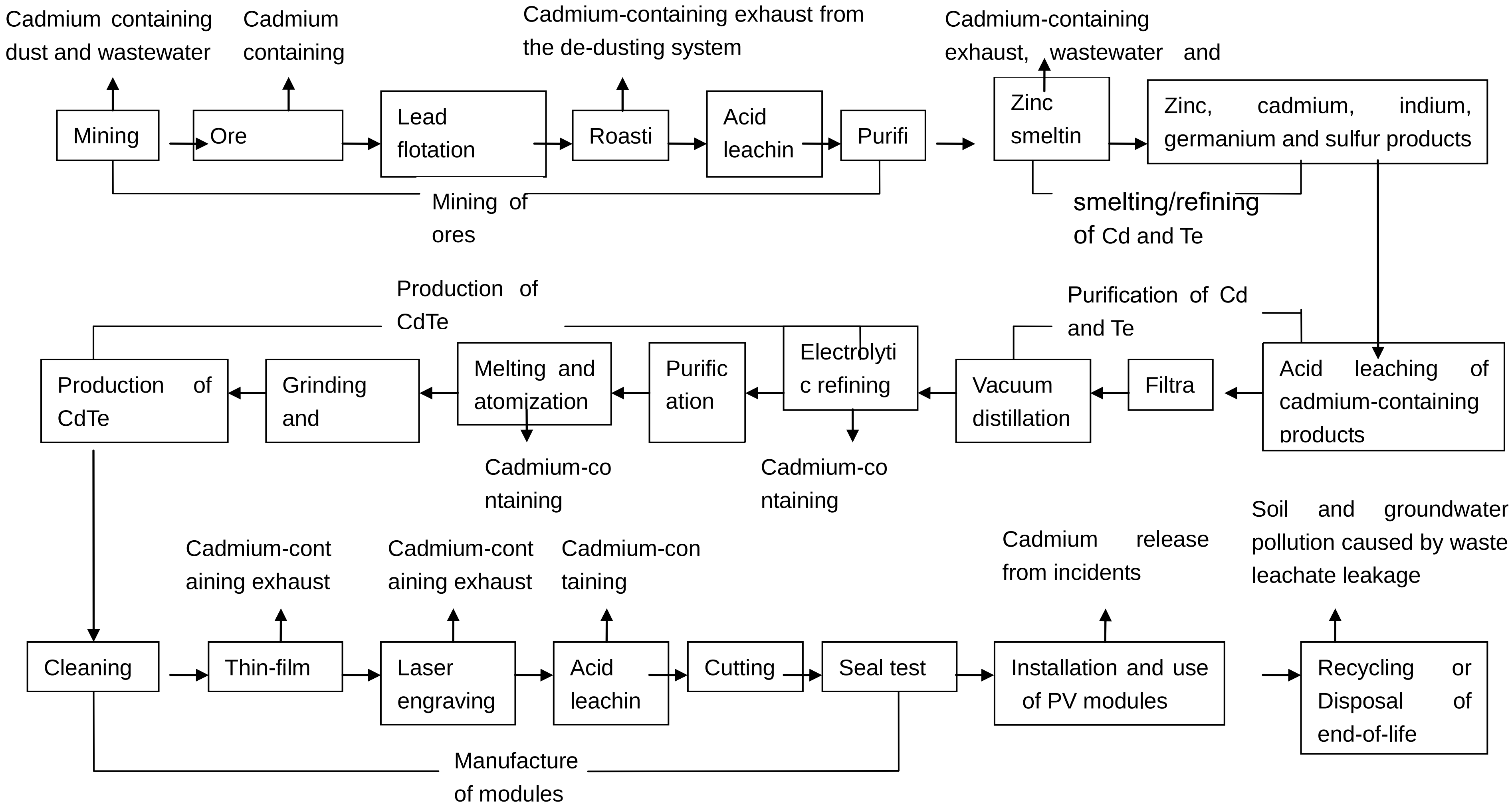

Appended drawing Analysis of cadmium emission processes in the lifecycle of CdTe PV

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

FINAL REPORT on FIRST SOLAR's CdTe PV TECHNOLOGY

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The final report was edited by Prof. Simo O. Pehkonen, Masdar Institute of Science and Technology.

EXECUTIVE SUMMARY

The following report (prepared and edited by Prof. Simo O. Pehkonen) consists of peer evaluation of the scientific literature regarding the environmental, health and safety (EHS) life cycle assessment (LCA) and resource availability aspects of FIRST SOLAR's CdTe PV technology. The following report extracted from the peer review team's opinions were based on the scientific articles and other materials provided by FIRST SOLAR, as well as the first workshop in Abu Dhabi, UAE on May 15, 2012 and an August 27, 2012 site visit to FIRST SOLAR manufacturing facilities (i.e., the First Solar KLM 5/6 Facility) in Kulim (Malaysia) and the second one-day workshop in Penang (Malaysia) on August 28, 2012.

The key findings of the peer review support the notion that CdTe PV technology can contribute to large-scale deployment of renewable energy solutions in an environmentally sustainable way addressing the increasing global demand for low-carbon energy. Specifically, it was found that (i) the emissions of Cd compounds into the ambient environment during the entire PV module lifecycle are minimal, (ii) that CdTe has been shown to be far less toxic than elemental Cd, (iii) that it is possible to ensure worker and environmental safety by implementing best practices for monitoring and management systems at CdTe manufacturing facilities. In addition, some of the positive environmental attributes of CdTe PV technology include a lower carbon footprint than crystalline silicon-based solar technologies considering the entire cradle-to-cradle life cycle and by extension a relatively short energy-payback time compared to other competing technologies. The potential for cradle-to-cradle of CdTe solar module recycling is significant (with more than 95% material recovery rates). This recycling potential, in addition to the untapped Te recovery sources from copper production, indicates that Tellurium availability is not expected to pose a threat to large-scale deployment of CdTe PV systems.

Table of Contents

Results

The results of the peer review team (its membership is shown below) evaluation are presented in two parts: Part I focuses on results summary based on the review of the scientific literature that took place in the summer of 2012 after the first workshop held in Abu Dhabi on May 15, 2012, where the scientific articles and summary reports were provided by FIRST SOLAR and discussed in some detail, while Part II focuses on results summary after the August 27, 2012 site visit to FIRST SOLAR's manufacturing facilities in Kulim (Malaysia) and the second one-day workshop in Penang (Malaysia) on August 28, 2012.

SUMMARY OF THE EVALUATION OF THE SCIENTIFIC JOURNAL ARTICLES

The evaluation of the 21 scientific journal articles and summary reports encompassing various aspects of CdTe PV (and other PV) Environmental, Health and Safety (EHS), LCA and resource availability issues provided to us by FIRST SOLAR was carried out by the following experts[1]:

Professor Abdulrahman A.R.M. Alamoud, King Saud University, Saudi Arabia

Dr.-Ing. Hasan Al Busairi, RENAC AG, Kuwait / Germany

Prof. Ahmed Al-Salaymeh, University of Jordan, Jordan

Dr. Raed Bkayrat, King Abdullah University of Science and Technology, Saudi Arabia

Prof. Mohammad Hamdan, University of Jordan, Jordan

Dr. Ibrahim Odeh, University of Jordan, Jordan

Prof. Mohammed Al-Sarawi, Kuwait University, Kuwait

Prof. Simo Pehkonen, Masdar Institute of Science and Technology, United Arab Emirates

Dr. Sgouris Sgouridis, Masdar Institute of Science and Technology, United Arab Emirates

Part I – Literature Evaluation

In general, the 21 articles (a list of them is shown at the end of this report as references 1-21) and summary reports were deemed relevant and generally well-written and support the notion of safe and environmentally sustainable production of electricity by CdTe (and other) PV technologies (the ranking summary is in Appendix 1). This conclusion can be drawn considering various aspects of the PV technology, including land use by PV compared to other energy production technologies, payback times, environmental footprint (from cradle-to-cradle) as well as the minimal release

[1] Contact information is presented in Appendix 3

of greenhouse gases, other EPA air pollutants and toxic substances (e.g., Cd compounds into the environment). Moreover, the recycling of used solar panel modules will further reduce (practically to zero) the risk of any toxic materials being released from the modules to the environment after their decommissioning.

From the toxicological studies, it is apparent that thorough additional studies focusing on the toxicity of CdTe, rather than relying on the "read-across" approach from data of very different Cd-containing compounds, should be carried out to minimize uncertainties in this regard. The performance of the CdTe PV modules in hot and dusty climates has also been determined and it turns out that the performance deterioration of CdTe PV modules as compared to Si based ones is less severe as a function of increasing temperature. The long-term (i.e., over the course of several years) performance and stability of CdTe PV modules in hot climates has also been assessed and the data (although based on a relatively small number of modules) is supportive of the stability of the modules over time.

Only 2 % of the studies reviewed received a "poor" ranking - mainly due to repetition of previous findings, i.e., the studies were deemed not novel. 14% of the studies have been evaluated with an overall evaluation of "fair" regarding clarity/appropriateness, quality and impact. The clear majority of the studies (i.e., 84%) have been evaluated with a "good" (35%) or "outstanding" (49%) clarity/appropriateness, quality and impact, the three categories that were being asked to be evaluated by the aforementioned experts (Appendix 2). Finally, the response rate was high and most reviewers responded to most articles/reports with a favorable impression in the aforementioned three categories

Summary of a few key articles is shown in the table below (Table 1).

It is important to select the two highest ranked articles among those reviewed, the first one is by **Fthenakis, V.M. et al. titled Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires.** The second highly-ranked article (written by the same lead author as the first one) is by **Fthenakis, V.M. titled Life Cycle Impact Analysis of Cadmium in CdTe PV Production.** Perhaps the weakest article among those reviewed was deemed the one by **de Wild-Scholten, M., and Schottler, M. titled Solar as an Environmental Product.**

Table 1. Summary of two excellent and one poor scientific article.

Title	Specific Comments
Fthenakis, V.M. et al. titled Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires	This article unequivocally proves the minimal release of cadmium from the CdTe PV modules during fires. This scenario has often been cited as a possible pathway of Cd into the environment. The score for this article was 21 (outstanding) and 3 (good). "Only a tiny portion of Cd (or Te) was released in the typical residential fire temperature (700-900 °C). Total Cd emissions during the whole life cycle of CdTe PV modules are estimated to be about 20 mg/GWh." "Very important with regard to emissions from incidents. Remaining 0.4% of emissions from the fire are not considered." "It addresses the emission and encapsulation of CdTe PV during fire in a well-designed approach"
Fthenakis, V.M. titled Life Cycle	"A good impact article showing the small amount of Cd released."

Impact Analysis of Cadmium in CdTe PV Production.	"The paper indeed is focused on one the most important barrier: cadmium flows and cadmium emissions into the environment, and compare the findings with those of Ni–Cd batteries and of coal fuel in power plants." "The manuscript is effectively and definitely answering questions related to the potential environmental impact of CdTe PV production. It addresses one of the most crucial issue: the emissions from CdTe during its life cycle."
Wild-Scholten, M., and Schottler, M. titled Solar as an Environmental Product.	"Deals mainly with carbon footprint and as such I believe it is irrelevant to our subject." "Not enough detail presented. Good point of material availability not explored further. Same for sourcing of Si (carbon intensity of China)."

Part II – Technology Evaluation

Finally, answers to the following **two key questions** below were generally positive with a couple of additional comments shown below.

1. 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)?

The overall consensus answer to the above question was **Negligible to no risks.**

Moreover, the following comment by the peer review team member was made to further support the above answer:

"The enclosed nature of CdTe between glass and/or plastic sheets minimizes the release of materials. Even during fires, glass (in a molten state) will encapsulate the CdTe compound. Alternative energy production methods (such as natural gas, oil and coal) release much more heavy metals (including Cd) into the environment."

2. What are the overall lifecycle 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 overall consensus answer to the above question was **Positive impacts or Significant positive impacts.**

Moreover, the following comment by the peer review team member was made to further support the above answer:

"The PV use of Cd actually transforms this potentially toxic metal into a safe and difficult to be released form (as compared to e.g., NiCd rechargeable batteries where Cd is present as oxides or hydroxides), recycling of panels is also key in this regard. Do note that Cd is a by-product of more widely used metals' mining and processing etc. (i.e., Zn, Pb and Cu) and Te a by-product of Cu production."

SUMMARY OF FIRST SOLAR MANUFACTURING, EHS AND RECYCLING PRACTICES AS WELL AS EVALUATION OF RESOURCE AVAILABILITY FOR CdTe PV TECHNOLOGY

The following topics (Parts 3 and 4 in the overall questionnaire) with the relevant questions/statements addressing them were answered/assessed by the peer review team after a site visit to Kulim, Malaysia First Solar manufacturing facilities as well as several presentations and roundtable discussions that took place in Penang, Malaysia on August 27-28, 2012.

In addition to the two key questions answered below, the site visit to Kulim (Malaysia) First Solar manufacturing site provided excellent information about the performance evaluation protocols and testing procedures that First Solar undertakes to simulate various weather and irradiation conditions in environmental test chambers. The chambers can vary relative humidity, temperatures and irradiation intensities to simulate all possible conditions encountered on solar power plant sites employing First Solar PV modules throughout the world.

Part III: Evaluation of CdTe PV manufacturing and recycling EHS policies and practices as implemented by First Solar

The peer review members felt that the best practices for EHS policies as implemented in the First Solar facilities were more than sufficient to ensure compliance with the most stringent work environment and ambient pollution regulations. All in all the questions related to the EHS, recycling and related policies of FIRST SOLAR CdTe PV were answered either by 4 (excellent) or 3 (very good) in terms of the best practices toward workplace safety (or EHS), manufacturing methods and facilities, recycling of CdTe PV panels, etc.

Some of the representative comments regarding the observed EHS, recycling issues, etc. provided by the peer review team are shown below:

> *"The visit to Kulim (Malaysia) facilities was very informative and the site visit along with presentations (both Monday and Tuesday) provided additional evidence of the stringent (more stringent than that required by law in the countries FIRST SOLAR operates) EHS procedures, monitoring of workers for blood cadmium levels, etc., the installation of HEPA filtration systems in many locations of the plant and the monitoring of indoor air Cd concentrations using various sampling devices, some of which mimick the human respiratory system very well. It is also noteworthy that the levels of blood Cadmium in workers have not statistically increased and in fact there are sources of Cadmium to the human (including FIRST SOLAR employees) body, such as smoking cigarettes and eating certain foods, that are likely much larger sources of Cadmium to the body than working in the very well-monitored and protected (using high-tech equipment) plant environment in Kulim and other FIRST SOLAR manufacturing facilities in the world."*

> *"First Solar has demonstrated leadership best practices in LCC and EHS of its CdTe modules. The manufacturing plants are state-of-the-art and represent a high level of automation, devices and tools in place to track the air quality continuously in the manufacturing area along with a continuous tracking of the Cd level in the employee bodies. Integrating systems for module recycling from the plant as well as from the field along with waste water*

recycling to minimize water usage are best practices and effective ways for reducing the overall carbon foot print."

"I had a chance to visit the First Solar Factory in Malaysia. All items above which they got a grade 4 from my side which is equivalent to Outstanding were proved to me during the lab tour in the factory and I am personally noticed this facts. I am really was impressed with the First Solar policies, practices, and management systems."

Part IV: Evaluation of resource availability for large-scale deployment of CdTe PV Systems

On the resource availability questions of both Cd and Te upon large-scale deployment of CdTe PV systems, the responses were generally favorable to the posted statements with two exceptions (shown below).

There were some questions on resource availability (with a rating of 2(= fair) each) on two posted statements *shown below inside parentheses*:

The first one is with regard to the availability of Tellurium and the second one is on the estimates of reserves (and an increased definition of reserves).

"Raw material scarcity in general and Tellurium availability in particular will not pose a threat to large-scale deployment of CdTe PV Systems."

"Current reserves estimates include a considerable level of uncertainty and an increased definition of reserves would be motivated by the economics of materials extraction."

A few representative comments to elaborate the above points were also included by the peer review team and they are shown below:

"Cd as well as Te are by-products of major mining operations such as Copper and Zinc. Also, research has shown the possibility of harvesting Te from other resources such as marine sources and mineral refining operations. The availability of Cd and Te will not be an issue from a theoretical stand point but might become more of an issue based on market conditions of supply and demand, where by other industries might support the demand on Cd and Te and improve market availability for all players in this field. In short, it is quite fair to say that over the next 20 years or so, there should be no issue in having adequate quantities of Cd and Te to support the expected market share for FS."

"Currently the raw materials are available in sufficient quantities and there is no threat at all. However, in the future and in the case of increased demands on these materials, then there is a possibility of such a threat."

"The issue of resource availability is always linked to assumption based forecasting, uncertainties are enhanced by technology trends related to demand for resources. Material and cost efficient recycling programs could reduce the impact of uncertainties for long-term plans, hence investment in recycling programs is essential for long-term stability of resource availability."

OVERALL CONLUSIONS OF THE PEER REVIEW ASSESSMENT

- No considerable risk can be seen under normal conditions and during foreseeable accidents. Potential exposure to Cd from rainfall induced leaching of broken modules or emissions due to a fire are highly unlikely to pose a health risk to the surroundings. Almost all (99.5%) Cd content in PV modules is encapsulated in the molten glass matrix during fires. Moreover, if CdTe PV modules are recycled or properly disposed at regulated municipal landfills at the end of their life, atmospheric Cd emissions during and after decommissioning will be negligible or zero.
- The usage of CdTe in PV applications may be regarded as beneficial to the environment by sequestering a considerable amount of cadmium, which is a waste product of Zn write in full production.
- CdTe consumes less energy than Si in the PV manufacturing process stage and material recycling would significantly reduce this primary energy demand.
- PV applications could be considered as less disturbing on land than fossil-fuel cycles if their expansion is not repurposing agriculturally productive land.
- The use of CdTe PV can contribute to the mitigation of greenhouse gas emissions.
- There is still a lack of comprehensive toxicological and eco-toxicological information on CdTe and further studies are needed to provide risk assessment approaches, although CdTe has been shown to be far less toxic than Cd.
- CdTe state-of the art practices for monitoring and management systems can sufficiently protect workers' health and safety as well as the environment at its manufacturing facilities.
- Further studies are needed on cadmium and tellurium resource assessment to better understand the relationship between materials demand and supply and the effect (of supply and demand?) on price escalation.
- Overall, CdTe PV technology represents an important technology in large scale deployment of renewable energy solutions to ever-increasing global energy demand.

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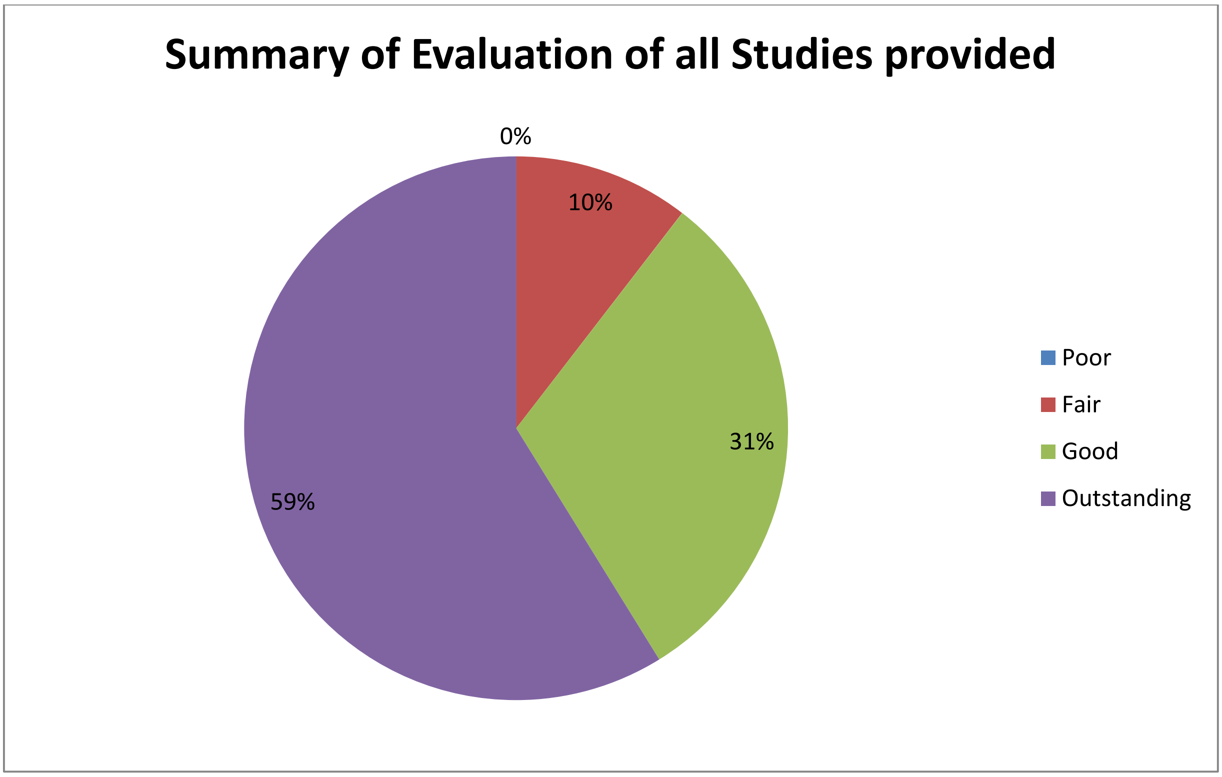
Appendix 1. Summary of evaluation of scientific journal articles

Research Paper	Evaluation (maximum score: 27 reviewer votes)					
	Poor	**Fair**	**Good**	**Outstanding**	**No vote**	**Σ**
(1) Fthenakis, V.M., Life Cycle Impact Analysis of Cadmium in CdTe PV Production	**0**	**0**	**5**	**19**	3	**24**
(2) Fthenakis, V.M., Kim, H.C. and Alsema E., Emissions from Photovoltaic Life Cycles	**1**	**2**	**3**	**15**	6	**21**
(3) Wild-Scholten, M., and Schottler, M., Solar as an Environmental Product	**1**	**12**	**6**	**3**	5	**22**
(4) Held, M., Life Cycle Assessment of CdTe Module Recycling	**0**	**4**	**9**	**11**	3	**24**
(5) Fthenakis, V., and Kim, H.C., Land Use and Electricity Generation	**0**	**1**	**10**	**13**	3	**24**
(6) Raugei, M., and Fthenakis V., Cadmium Flows and Emissions from CdTe PV	**1**	**3**	**9**	**11**	3	**24**
(7) de Wild-Scholten, Mariska, Environmental Profile of PV Mass Production	**1**	**3**	**10**	**10**	3	**24**
(8) Zayed, P., and Philippe, S., Acute Oral and Inhalation Toxicities in Rats with Cadmium Telluride	**1**	**4**	**4**	**15**	3	**24**
(9) Harris, et al., The General and Reproductive Toxicity of the Photovoltaic Material Cadmium Telluride	**3**	**7**	**11**	**3**	3	**24**
(10) Kaczmar, Swiatoslav W., Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics	**0**	**4**	**12**	**8**	3	**24**
(11) Fthenakis, V.M. et al., Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires	**0**	**0**	**3**	**21**	3	**24**
(12) Sinha, Parikhit, Robert Balas, und Lisa Krueger, Fate and Transport Evaluation of Potential Leaching and Fire Risks from CdTe PV	**0**	**1**	**9**	**14**	3	**24**
(13) Mennenga et.al., Berechnung von Immissionen beim Brand einer Photovoltaik-Anlage aus Cadmiumtellurid-Modulen	**0**	**1**	**10**	**11**	5	**22**

(14) Tvermoes, Brooke E., Marianna Anderle de Sylor, Jennifer Sahmel, William Cyrs, und Dennis J. Paus-tenbach, An Assessment of the Possible Hazards From Disposal of Cadmium Containing Thin-Film Photovoltaic (PV) Modules in Municipal Landfills	**0**	**6**	**7**	**11**	3	**24**
(15) Candelise, Chiara, Mark Winskel, und Robert Gross, Is Indium and Tellurium Availability a real concern for CdTe and CIGS Technologies?	**2**	**3**	**9**	**10**	3	**24**
(16) Andersson, Bjoern A., Materials availability for large-scale thin-film photovoltaics	**0**	**3**	**14**	**7**	3	**24**
(17) Zweibel, K., The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics	**0**	**6**	**12**	**6**	3	**24**
(18) Summary Report, Peer Review of Major Published Studies on the Environmental Profile of Cadmium Telluride (CdTe) Photovoltaic (PV) Systems	**0**	**2**	**6**	**14**	5	**22**
(19) Summary Report, Environmental, Health, and Safety (EHS) Aspects of First Solar Cadmium Telluride (CdTe) Photovoltaic (PV) Systems	**0**	**2**	**4**	**14**	7	**20**
(20) Executive Summary, First Solar CdTe Photovoltaic Technology: Environmental, Health and Safety Assessment	**0**	**1**	**8**	**12**	6	**21**
(21) Summary Report, Environmental, Health and Safety Impact Evaluation of CdTe PV Installations Throughout Their Life-cycle	**0**	**3**	**8**	**11**	5	**22**
Σ	**10**	**68**	**169**	**239**	**81**	**486**

Appendix 2. Summary of evaluation of all studies provided



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December 1, 2013

Environmental risk assessment of CdTe PV systems to be considered under catastrophic events in Japan

Dr. Yasunari Matsuno, Associate Prof., The University of Tokyo, Japan

1. The Goal and Scope

The purpose of this report is to summarize the environmental risk assessment of CdTe PV systems to be considered under potential catastrophic events in Japan. Earthquakes, tsunami and big fires caused by tsunami are some of the catastrophic events which are of most concern in Japan. So, the potential environmental risks caused by these disasters should be considered for CdTe PV systems, and the mitigation method to minimize the risks should be clarified. This review is undertaken at the request of First Solar.

2. Huge disasters to be considered for CdTe PV systems in Japan:

An earthquake is a potential catastrophic event of particular concern in Japan. It is still fresh in our minds that a massive earthquake hit the north-east of Japan and triggered a tsunami that had caused extensive damage on March 11th, 2011. In addition, the tsunami caused big fires at 177 places in Japan. These big fires also had occurred in the big earthquakes and subsequent tsunami in the past[1]. The main sources of the big fires were the reservoirs of fuel and liquefied petroleum gas (LPG) located along the coast that had been damaged by the tsunami[2].

Since many cities are located along the coast, earthquakes, subsequent tsunami and fires are catastrophic events of particular concern in Japan, which should be considered for CdTe PV systems.

Fig. 1 Large fire caused by tsunami in Kesenuma City on March 11, 2011[2]

3. Hazard map data for earthquakes and tsunami

Ministry of Land, Infrastructure and Transport and Tourism, Japan releases “Hazard Maps” for earthquakes, and tsunami, etc. which cover many regions in Japan. They are available on Web site[3, 4] (in Japanese):

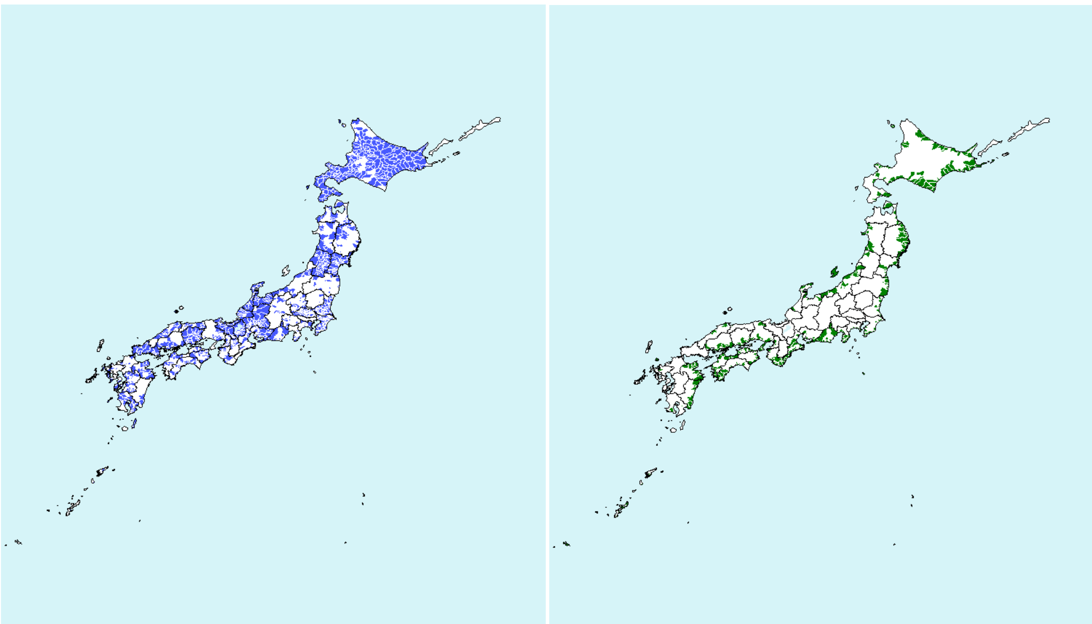
Fig. 2 Hazard map availability for earthquake (left) and Tsunami (right)

The details and data availability for these hazard maps vary in regions (cities and towns). Some examples of hazard maps for earthquake and tsunami of Cities in Tohoku area are shown in Figs. 3(a)-(b).

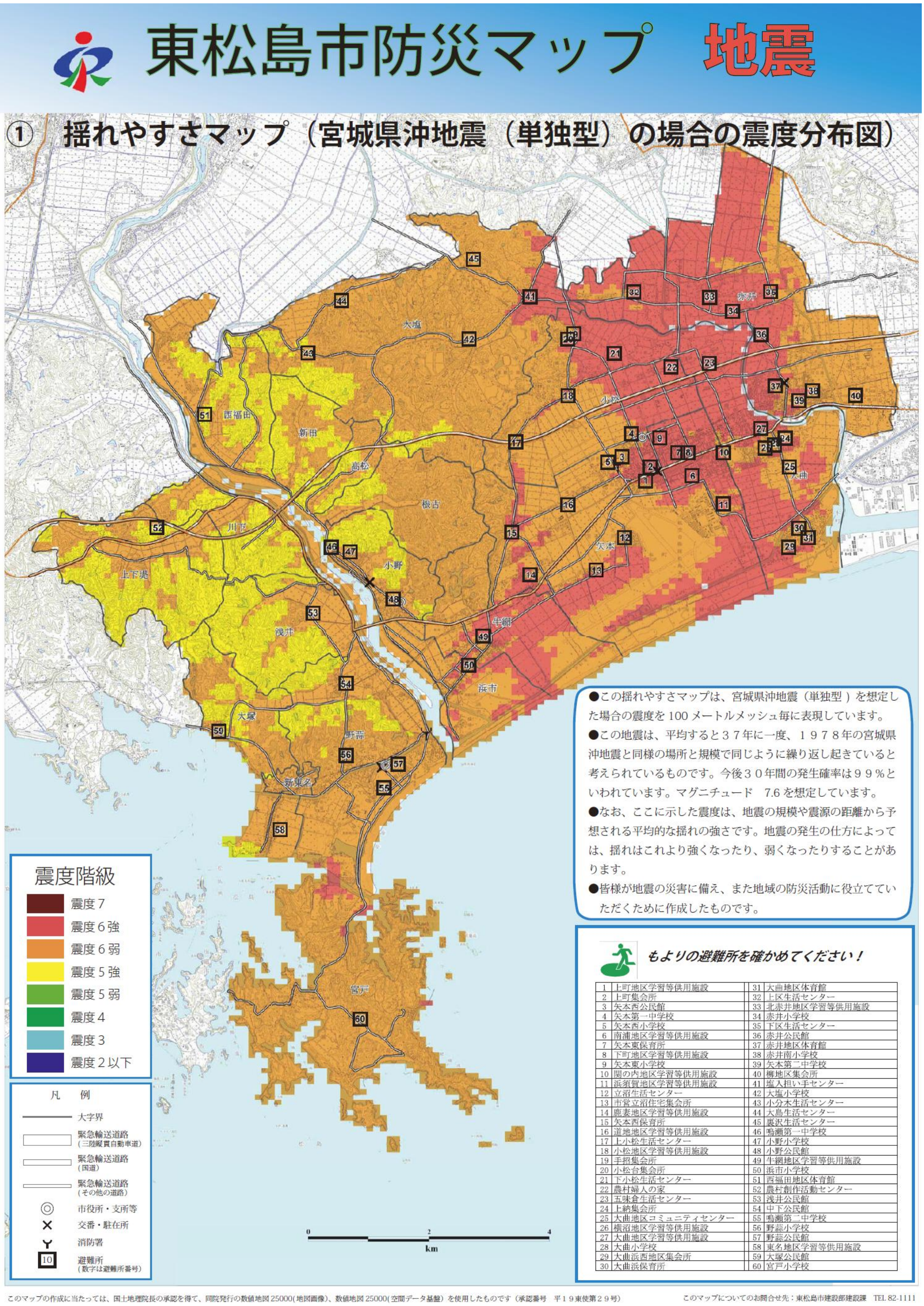

Fig. 3(a) Earthquake Hazard Map for Higashi-Matsuyama City – Seismic Intensity Map for the case of Reoccurrence of the 1978-type Miyagiken-Oki Earthquake

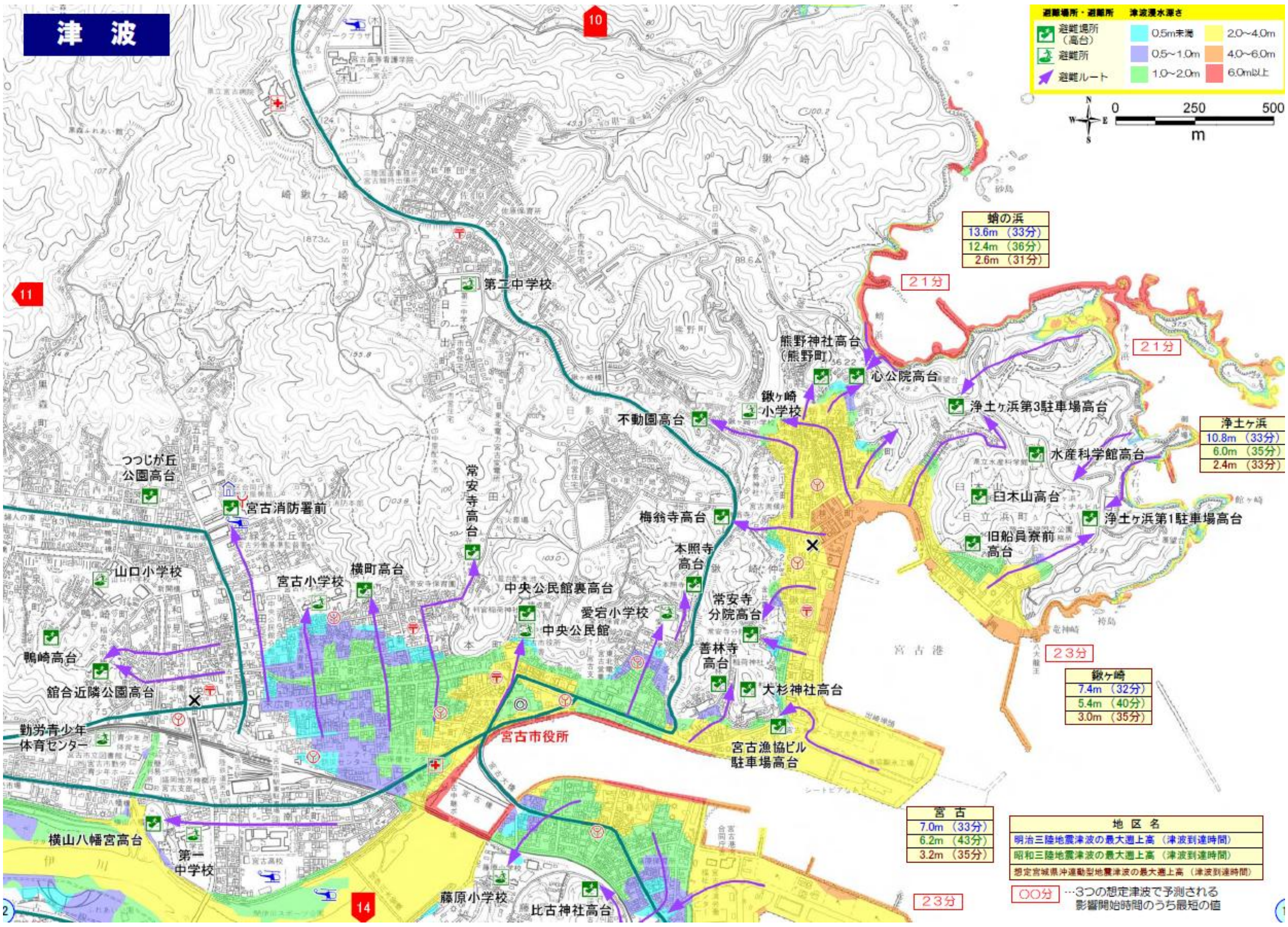

Fig. 3(b) Hazard Map for Tsunami of Miyako city

4. Evaluation of environmental risks of potential catastrophic events and the mitigation methods to minimize the risks

Environmental risk assessment is the standard scientific method for evaluating potential health and environmental impacts from exposure to chemicals in the environment (Fig. 4).

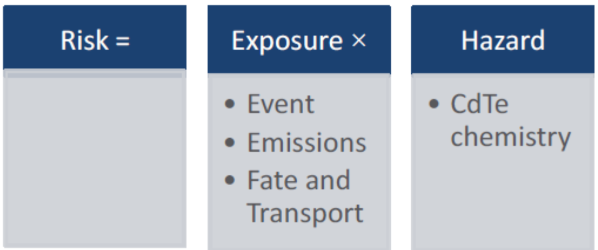

Fig. 4 Environmental risk assessment framework

Use of heavy metals (e.g., Pb, Cr, Cd compounds) is commonplace in the PV industry. The environmental risk related to each catastrophic event involving CdTe PV systems is discussed below.

4.1 Earthquake

Environmental risks for PV modules impacted by an earthquake would be related to the breakage of the modules in the impacted geographic area.

CdTe is classified as insoluble in water due to an extremely low solubility product (9.5×10^{-35}). Even if modules become broken or damaged, CdTe would not mobilize from the glass and into the environment except under very specific conditions. One condition would be if glass modules are crushed to fine pieces (< 1 cm) and then subjected to agitation in an acidic environment. These conditions would not occur in the field during any project operations[5].

Experimental evaluation of CdTe mobility in pure compound form has been conducted with transformation and dissolution testing. The testing is designed to determine the rate and extent to which sparingly soluble metal compounds can produce soluble available ionic species in aqueous media under a set of standard laboratory conditions representative of those generally occurring in the environment. Specifically, the testing measured the concentration of Cd resulting from a 1 mg/L loading of CdTe after 28 days in a standard aqueous medium at pH 6. 15 µg/L Cd resulted from 1 mg/L CdTe loading, corresponding to approximately 1.5% solubility[6).

Note that the transformation and dissolution test results are for the pure CdTe compound, whereas in CdTe PV, CdTe is bound under high temperature to a sheet of glass by vapor transport deposition, coated with an industrial laminate material, and covered with a second sheet of glass. The module design results in the encapsulation of the semiconductor material between two sheets of glass thereby preventing the exposure of CdTe to the environment under normal conditions, and greatly reducing potential exposure under broken-module conditions.

In addition, First Solar's PV Module Performance Detection and Handling Plan that have been used in the large-scale CdTe PV projects in the western U.S[7) may be able to identify, handle, and remove broken PV modules after the earthquake. Specifically, routine inspections and power output monitoring can diagnose broken modules for prompt removal. These measures will further mitigate the environmental risks of CdTe PV systems.

4.2 Tsunami

Potential risks for PV modules impacted by a tsunami would be related to the scattering of the modules over the impacted geographic area. For metals in general, environmental mobility is a function of pH, with decreased mobility at higher pH. Because sea water is alkaline (Fig. 5) with pH in the global ocean surface waters ranging from 7.9 to 8.2[8), metal solubility would be expected to be limited for modules dispersed in sea water. In addition, even when fully dissolved (at aquatic saturation), aquatic toxicity testing of CdTe showed no ecological health effects on the standard zebrafish test species[6). To further quantify the potential impacts of tsunami on CdTe PV modules, First Solar conducted leaching tests with seawater as a solvent[9).

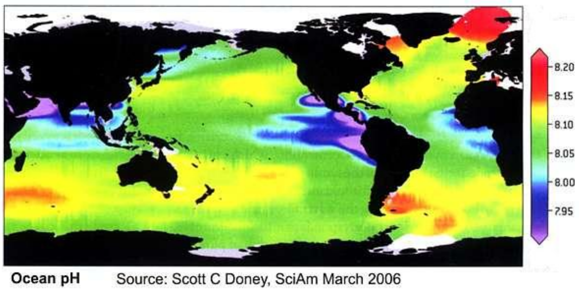

Fig. 5 Variations in pH in sea water

4.2.1 Seawater Leaching Test[9)

The experimental method for the seawater leaching test made use of the DIN standard batch leaching test modified with synthetic seawater as a solvent. The potential impacts are considered for module fragments in still sea water conditions, such as a flooded inland area of low elevation. In such condition, there is no current so module fragments would settle and not undergo continuous tumbling. To reflect this scenario, the seawater leaching test was conducted without tumbling. (Table 1)

In accordance with a 10:1 liquid/solid ratio, 90 grams of 9 mm by 9 mm PV module samples were subjected to 900 mL of seawater solution for 24 hours. After this period, the sample solution was filtered (45 µm filter) and acidified using HNO_3 to bring the solution below 2 pH, followed by analysis of Cd with ICP-MS. Five samples were tested with results ranging from 17-37 µg Cd/L per 24 hr. (Table 1)

Table 1 Analytical results of seawater leaching test for CdTe PV modules with DIN batch leaching test modified with synthetic seawater as a solvent and with no tumbling for closed sea water scenario

LAB #	Sub ID	Cd (ppb)	Pb (ppb)	specific gravity	Temp before (deg C)	pH before	conductivity before (uS)	Post Temp	post pH	post conductivity (uS)
AA63862	130925261888	17	<5	1.0225	20.7	8.17	46400	21	8	42900
AA63863	130925261885	37	<5	1.0225	20.7	8.18		20.4	8.22	43600
AA63864	130925261886	19	<5	1.0215	20.3	8.17		20.5	8.22	42800
Acid Blank		<10	<5	1.0215	20.3	8.17		20.5	8.18	43600

With the measured Cd concentration in seawater leachate ranging from 17-37 µg Cd/L, the percentage of dissolved Cd to the total CdTe was estimated as approximately 0.03%/day.

4.2.2 Interpretation of potential environmental risks caused by tsunami

In the case of tsunami, broken module pieces may be dispersed in seawater. To evaluate the potential environmental risks caused by tsunami from the results of the leaching tests, a scenario of 1 MW of PV module fragments in closed sea water was considered.

The potential impacts were estimated based on the following equation.

$C = (T \times E) / V$

C: Incremental Cd concentration (µg/L/day)
T: Total CdTe content (µg)
E: Cd emissions fraction (%/day)
V: Volume of seawater (L)

For parameter "T" based on 13% efficient PV modules, there is approximately 0.127 g CdTe per W (1.27×10^{11} µg CdTe per MW). For parameter "E", the measured Cd concentration in seawater leachate in Table 1 corresponds to a percentage of dissolved Cd to the total CdTe of approximately 0.03%/day. For parameter "V", a 1 MW installation requires approximately 2 hectares (20,000 m^2). If this area is flooded with 2 m of seawater, the total volume of seawater is 40,000 m^3 (40,000,000 L). Based on these parameters and the equation, the average incremental concentration of dissolved Cd in the total volume of closed seawater is approximately 0.95 µg/L/day. However, it should be noted that these results can be considered to reflect the worst case scenario in which all of the PV modules would be broken into small pieces, i.e. 9 mm by 9 mm pieces, by tsunami and submerged in a closed seawater. Therefore, it is likely that the average incremental concentration of dissolved Cd in the closed seawater is significantly lower than 0.95 µg/L/day.

In Japan, environmental quality standards for water pollutants - environmental quality standards for the human health has been set as 3.0 µg/L for Cd. This standard is based on the annual mean and can be considered for chronic (long-term) exposure. The environmental quality standard for Cd to conserve aquatic life has been discussed, but not established in Japan[10)]. In addition, there is no distinction in the standards for acute (short-term) exposure and chronic (long-term) exposure. In contrast, US EPA has established national recommended water quality criteria for the protection of aquatic life and human health in surface water for approximately 150 pollutants including Cd, in which criteria have been distinguished for acute and chronic as well as freshwater and saltwater[11)]. Since leaching of Cd from broken PV modules by tsunami is an accidental release, it can be considered as an acute (short-term) exposure. Therefore, if we compare with U.S. EPA's acute limit of 40µg/L, Cd concentration in sea water which contain submerged PV module after tsunami will not exceed the aquatic screening criteria for a certain (long) period.

Nonetheless, it should be recommended that the prompt recovery of submerged PV modules should be conducted to minimize the leaching of Cd.

4.3 Big fires caused by tsunami

Beckmann and Mennenga investigated[12)] the effects of CdTe modules on the neighborhood and the general public in the case of fire. They estimated Cd concentrations in air on the surface around the burning CdTe PV modules. In the worst case, the Cd concentration in air from a fire with the largest area (1,000 m^2) with the maximum Cd contents (66.4 g/m^2) and at the shortest calculable distance (100 m) from the emission site was calculated. However, the result (0.66 mg/m^3) was still substantially below the acute exposure guideline level, AEGL-2 (10 min.) of cadmium, 1.4 mg/m^3, which is the peak concentration value for the threshold to irreversible effects or other severe, long-lasting health effects[13)].

It should also be noted that they assumed in their calculations that all Cd contained in the module was released completely from the CdTe compound as Cd fumes. Reaction with CdO or a possible diffusion of cadmium in the molten glass was not considered in determining the Cd emission concentrations. Fthenakis et al. investigated CdTe modules, which were heated to temperatures ranging from 760° C to 1,100° C, typical for fires in residences and service buildings, and showed that more than 99% of the Cd remained within the molten glass matrix[14)]. In addition, as mentioned in 4.2.2, First Solar's 13% efficient PV modules contain significantly small Cd content, approximately 7.7 g/m^2. Therefore, it is quite likely that Cd concentration in air on the surface around the burning CdTe PV modules will be quite small compared with the acute exposure guideline level.

There are uncertainties whether and where big fires will occur after tsunami, how long they last, and whether CdTe PV modules will be subject to the big fires or submerge in sea water. So, PV modules may not necessarily be subject to the big fires. Therefore, the environmental risks of CdTe PV systems by big fires caused by tsunami can be considered very small.

4.4 Other previous works related to the environmental risks of CdTe PV systems

Central Research Institute of Electric Power Industry, Japan investigated the environmental risks of CdTe PV systems in the fiscal year of 1998 with the financial support by NEDO, in which Cd emissions in cases of fire and leaching of Cd from broken modules were investigated[15)].

The combustion tests were conducted to measure the volatilization rate of Cd from various CdTe thin-film PV modules at 750-1000 centigrade. The volatilization rates of Cd from the modules were measured as <0.25% at 800-1000 centigrade. These results were used to estimate the Cd concentration in a plume generated in a wooden house on fire as well as those on surfaces around the house. It was concluded that the estimated concentration was lower than the legally regulated value in either case.

The batch leaching tests were conducted with broken CdTe PV modules in the acid rain atmosphere (pH = 4.8, 40 centigrade) with continuous tumbling for 10 minutes to 72 hours. It was found that the Cd concentrations were below the minimum detectable quantity in all leaching tests. So, it was concluded that Cd leaching from broken CdTe PV modules in an ordinary atmosphere would be negligible.

From the all results mentioned above, it was concluded that there would be no problem to use CdTe PV systems from the view point of the environmental risks.

5. Conclusion

In this report, environmental risks of CdTe PV systems under catastrophic events in Japan were considered with a focus on earthquakes, tsunami and big fires caused by tsunami. There is a big uncertainty on how many CdTe PV modules will be broken in earthquakes, and in a subsequent tsunami, how many will be subject to big fires or be submerged in sea water. However, even in the worst case scenarios, it is unlikely that the Cd concentrations in air and sea water will exceed the environmental regulation values. So, the environmental risks of CdTe PV systems under catastrophic events can be considered small.

For commercial reasons, power systems are not likely to be constructed in tsunami hazard areas; nevertheless, the prompt recovery of broken and submerged PV modules should be conducted to minimize the leaching of Cd after earthquakes and tsunami.

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May, 2012

Scientific Review on the Environmental and Health Safety (EHS) aspects of CdTe photovoltaic (PV) systems over their entire life cycle

Dr. Yasunari Matsuno, Associate Prof., The University of Tokyo, Japan
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The Goal and Scope

The purpose of this review is to assess the Environmental and Health Safety (EHS) aspects of CdTe photovoltaic (PV) systems over their entire life cycle, including module manufacturing, module use, and end-of-life disposal. The review was undertaken at the request of First Solar, and was hosted by Associate Professor, Dr. Yasunari Matsuno, The University of Tokyo, accompanied by co-investigator, Prof. Dr. Hiroki Hondo, Yokohama National University.

The review consisted of the following two processes:

1) The reviewers investigated the written and presented materials related to the potential environmental, health, and safety risks and benefits associated with CdTe PV systems during their life cycle.

2) The lead reviewer visited the First Solar's Perrysburg, Ohio facility in the United States on May 2nd, 2012 to receive:

- A tour of the manufacturing and recycling facilities;
- Presentations on the EHS aspects of CdTe PV modules; and
- Presentations on the EHS practices in place at First Solar's manufacturing and recycling facilities.

At the end of the presentations, there was a roundtable discussion among the reviewer and presenters, and additional personnel. The roundtable discussion was to focus on two key questions defined below, as well as to give the reviewer the opportunity to discuss preliminary findings and ask additional questions. First Solar replied to the reviewer's questions and gave additional materials when necessary.

<u>Two key questions addressed during the roundtable discussion:</u>

1) 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)?

2) 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?

Conclusions

The main conclusions obtained in this review are the followings:

1) Environmental and Health Safety (EHS) aspects of First Solar's CdTe photovoltaic (PV) systems

・Concerning manufacturing operations, First Solar has continuously implemented outstanding policies, practices, procedures and management systems in order to protect worker's health and safety as well as the environment. Actual air and water emissions of cadmium are well below the local regulatory limits in all factories. First Solar is very proactive in developing and improving safety programs to further reduce risk and encourage the active participation of all employees. First Solar manufacturing plants are certified to ISO 9001(quality), ISO 14001 (environmental), and OHSAS 18001 (occupational, health and safety) standards.

・ Under normal operating conditions, there will be no emission from CdTe PV modules, which leads to no impact to environment, except for impacts from land use. However, it should be noted that the PV systems cause the least impacts by land use among renewable-energy options [16].

・ In the foreseeable accidents (e.g. fire, breakage of CdTe PV modules), the emissions of cadmium or cadmium compounds have been proven to be negligibly small. In a fire, almost all (99.96%) of the cadmium content of CdTe PV modules will be encapsulated in the molten glass matrix [2]. Module breakage rate is below 1% over 25 years (0.04%/yr), over one-third of which occurs during shipping and installation. In addition, routine inspections and power output monitoring diagnose broken modules for takeback and recycling [10].

・A recent study related to acute oral and inhalation toxicities in rats clearly shows that CdTe is less toxic than Cd [9]. The solubility and bioavailability of CdTe has also been shown to be much lower than other Cd compounds [5, 28]. One study has so far been conducted for ecotoxicity of CdTe, which investigated the acute aquatic toxicity of CdTe on zebrafish (*Brachydanio rerio*). The results show no toxic (lethal or sub-lethal) effect on fish at aquatic saturation [5, 29].

・ First Solar has introduced an excellent global Module Collection and Recycling Program that makes sure to collect and recycle the CdTe PV modules from the owners at no cost, whenever and wherever it is requested. This will further reduce the risks at the end-of-life stage [24-26].

・The frequency of huge disasters (e.g. large earthquake, fire, tsunami) in Japan is relatively large compared with those in other countries. However, no study for examining the risk of CdTe PV modules under such huge disasters has so far been published, though such issues have been partly considered in project permitting environmental impact reports [27].

2) Life cycle environmental impact of First Solar's CdTe photovoltaic (PV) systems

・ The life cycle GHG emissions and energy payback time of First Solar's CdTe PV technology, which are based on unit kWh electricity generation under normal operating conditions, are 19-30 g-CO_2/kWh and 0.7-1.1 years, respectively, depending on location of installation [18]. These values are the lowest among all current PV technologies [15]. Compared with fossil fired power generation, e.g. coal-fired and oil-fired power plants, GHG emissions of First Solar's CdTe PV technology per kWh of electricity generation are quite small [12].

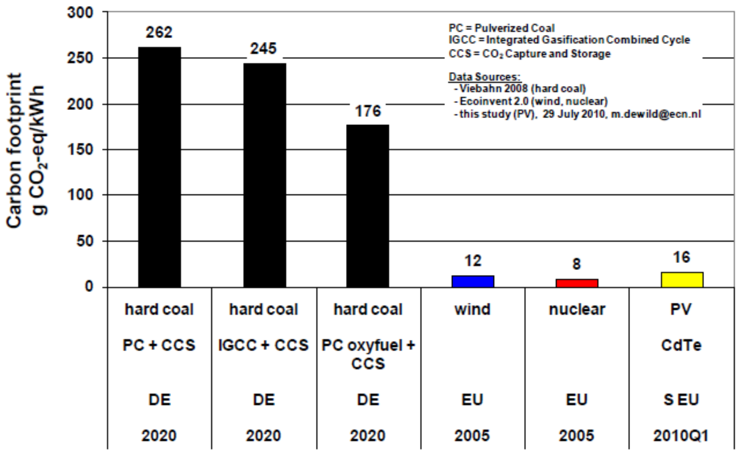

Fig. 1. From de Wild-Scholten (2010) [12]

・ All types of PV modules including Si PV have cadmium emissions in the production stage. For example, the electricity consumption in PV module production must lead to cadmium emissions from fossil fuel fired power stations. Like Si PV technology, First Solar's CdTe PV technology has lower cadmium emissions compared with coal and oil fired power generation during its life cycle[15].

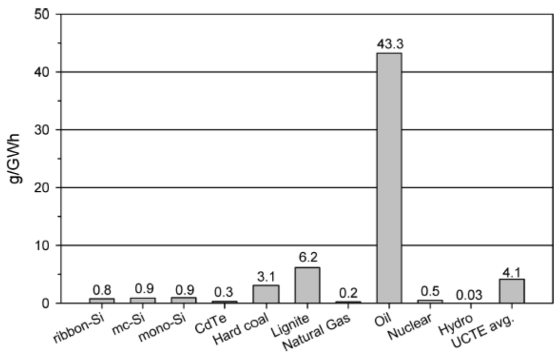

FIGURE 3. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 yrs. Ground-mounted BOS (*18*) is assumed for all PV systems; comparisons with other electricity generation options.

Fig. 2. From Fthenakis et al. (2008) [15]

・Cadmium emissions to air by CdTe PV module production contribute to 0.04% of the total damage to human health based on the life cycle impact assessment method

IMPACT2002+ [12].

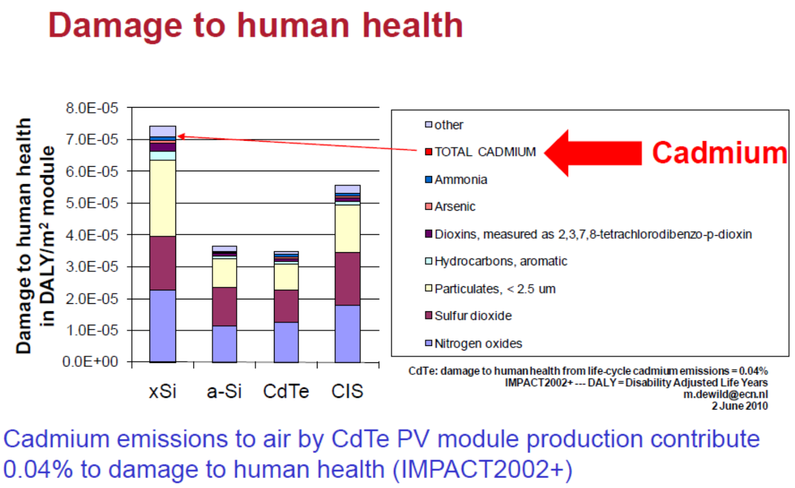

Fig. 3. From de Wild-Scholten (2010) [12]

· Cadmium is an unavoidable by-product of zinc smelters, and therefore the production of cadmium and cadmium emissions are inevitably affected by zinc demand. The studies related to dynamic modeling of cadmium substance flow with zinc demand revealed the potential for a cadmium oversupply problem in the near future, and the consequent need to develop alternative treatment methods for the cadmium surplus, including finding a sustainable use of cadmium [22]. CdTe PV systems that use cadmium as a raw material can be considered as one of the solutions in this regard [19].

Summary of conclusions

· Compared with coal and oil-fired power generations, both GHG and cadmium emissions of First Solar's CdTe PV technology per kWh of electricity generation during its life cycles are quite small under normal operating conditions.

· The study of dynamic cadmium substance flow analysis has pointed out the potential for a cadmium oversupply problem in the near future. CdTe PV systems that use cadmium as a raw material should be considered as one of the solutions for a sustainable use of cadmium.

· In foreseeable accidents, e.g. fire, breakage of CdTe PV modules, the emissions of cadmium or cadmium compounds have been proven to be negligibly small. In addition, First Solar has introduced an excellent global Module Collection and Recycling Program which further reduces the risks at the end-of-life stage.

· However, we believe that CdTe PV systems should be used only for large scale operations, and not be used for dissipative products (e.g. toys, household electronic products) In addition, the frequency of huge disaster (e.g. great earthquake, fire, tsunami) in Japan is relatively large compared with those in other countries. Therefore, CdTe PV systems should not be located close to sea level and hazardous facilities to avoid the risks under the huge disasters. It should be noted that, in general, all power plants, including fossil fired power plants, nuclear power plants, etc. have some potential risks in huge disasters.

Future researches to be recommended

- Ecotoxicity of CdTe and CdS should be evaluated more in detail on the test organisms such as pseudokirchneriella subcapitata and daphnia magna.

- The risks of CdTe PV systems under the huge disasters should be further evaluated.

- It is expected that the study about life cycle impacts of CdTe PV systems will be updated to include and reflect the First Solar's state-of-the art recycling processes (e.g. recycling of the filter cake) [11].

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Appendix 1 Questions by reviewers and replies by First Solar

Environmental and Health Safety (EHS) Risks

1) Toxicity of CdS

Zayed & Philippe (2009) and Kaczmar et al. (2011) evaluated the toxicity of CdTe. On the other hand, there is no toxicological information about CdS which is also used for CdT PV modules (de Wild-Scholten and Schottler, 2006). Do you have any information and data related to CdS toxicity?

Answers:

- CdS accounts for less than 3% of the total Cd in the module

- Less soluble than CdTe (< 1% solubility)

  - Long term transformation & dissolution testing with a 1 mg/L loading of cadmium sulfide showed a concentration of 5.75 µg of Cd per liter of water after 28 days

- Low acute oral and dermal toxicity

  - Classified as non-toxic for acute exposure

- Low respirable fraction (less than 10 µm) limits inhalation toxicity

  - Average particle size is 200 µm

2) Ecotoxicity of CdTe and CdS

Although Agh (2011) has conducted the acute toxicity tests of CdTe to zebrafish, there are little information and data about the ecotoxicity of CdTe and CdS. Besides Agh (2011), do you have any information and data concerning the ecotoxicity of these compounds? We also appreciate it if you could give us the papers by Agh (2011) because we cannot obtain these papers from our universities. Ecotoxicity for fishes is a great concern for Japanese because Japanese daily intakes of fishes are relatively large compared with those in other Western countries. Are zebrafishes appropriate species for testing acute toxicity?

Answers:

- For both CdTe and CdS, ecotoxicity (and bioavailability in general) is related to solubility (release of Cd^{2+} ion).
- The extremely low solubility of both CdTe and CdS results in reduced ecotoxicity

  - There were no effects (lethal or sublethal) from CdTe at aquatic saturation for zebrafish over 96 hrs; CdS has even lower solubility than CdTe.

· Ecotoxicity testing in Agh (2011) was performed according to OECD and USEPA test guidelines with zebrafish as the recommended test species

3) Accidents in PV manufacturing factories

We understand from First Solar's Document (2011) that First Solar has introduced an excellent EHS management system in its plants. However, although there is a very small probability, some accidents (e.g. fires, explosions) may happen during the operation of the plants. Have you ever investigated the potential risks and/or exposures of Cd or Cd compounds to your workers in your plants and/or residents near your plants when the accidents happen? We believe that plants who deal with toxic substances, e.g. Cd or Cd compounds should be equipped with measures for these accidents.

Answers:

· Bureau Veritas performed dispersion modeling of manufacturing plant fire emissions as part of EHS permitting for proposed First Solar manufacturing plant in Blanquefort, France, and the risk was found to be negligible.

· First Solar manufacturing plants are certified to:

- ISO 9001:2008 (quality), ISO 14001:2004 (environmental) and OHSAS 18001:2007 (occupational, health and safety) standards

4) Huge disasters

The studies by Fthenakis et al. (2005), Sinha (2011) and Steinberger (1998) show that cadmium emissions remain negligible in the exceptional cases, e.g. accidental fires or breakage of panels. On the other hand, the frequency of huge disaster (e.g. great earthquake, fire, tsunami) in Japan is relatively large compared with those in other countries. We believe that these huge disasters should be taken into account in environmental and health safety (EHS) aspects. Have you have ever investigated the effect of huge disasters on the EHS aspects of CdTe PV systems? We believe that CdTe PV systems should not be used for dissipative products nor located close to sea level and hazardous facilities, e.g. petroleum and petrochemical plants.

· Maximum wildfire temperatures (approximately 800-1000°C) are below the melting point of CdTe (1041°C), limiting release.

· Broken modules from earthquake are addressed by a PV Module Performance Detection and Handling Plan for identifying and handling broken PV modules and it is unlikely that broken modules associated with an earthquake would be left in the field for any significant amount of time. Additionally, the low solubility of CdTe minimizes risk, and modules do not shatter when broken, but rather the vast majority of breakage is manifested as hairline-cracks which leaves the module virtually intact.

· Routine inspections and power output monitoring diagnose broken modules for takeback and recycling.

· Risks for modules impacted by a tsunami would be related to the scattering of the modules over the impacted geographic area. The low solubility of CdTe and the design of the modules (laminated glass on glass) minimize the direct impact to the environment. Additionally, in comparison to traditional forms of electrical generation, the environmental impacts of a tsunami on a PV plant are low. Fukushima provides evidence of the impacts of nuclear power disaster, and a fuel oil spill and potential fires associated with fuel oil and natural gas power plants create a higher level of environmental risk.

Life Cycle Impacts

5) Detailed life cycle inventory data of PV systems

There have been many LCA case comparative studies for PV systems, e.g. Fthenakis et al. (2008), Held & Ilg (2011), de Wild-Scholten (2010), etc. The work by Held & Ilg (2011) was one of the studies base on the latest data, which pointed out the recent drastic changes in PV production system, including recycling processes.

In order to review their works, we request the detailed life cycle inventory (LCI) data for production of PV module, frame and BOS, e.g. the amount of electricity, fuels, and materials required and emissions of Cd, CdTe, CdS etc. to produce one unit of PV modules in First Solar plants. The changes of LCI in recent years should be clarified. In addition, Fthenakis et al. (2008) used the data from the "CrystalClear project" to conduct LCA for crystalline silicon modules. We appreciate it if you could offer the data because we cannot obtain them.

As Wild-Scholten (2011) mentions, the electricity grid mix has a significant effect on life cycle environmental impacts of PV. As far as we understand, First Solar has plants to produce PV modules in USA and Malaysia. The differences in environmental impact of electricity grid mix in these sites should be reflected in conducting LCA for First Solar's PV systems.

· LCI data for module, BOS, and recycling will be provided (note there is no frame).

· CrystalClear data can be found at:
http://www.ecn.nl/docs/library/report/2007/e07026-LCIdata-cSiPV-pubv2_0.xls

· Impact of grid electricity mix has been reflected in de Wild-Scholten (2011)

· CdTe is less sensitive than Si PV due to lower electricity use in manufacturing

6) Recycling of PV modules

6-1 First Solar's Module Collection and Recycling Program seems excellent. We are wondering whether there are any other companies who produce Si-based PV systems that have similar programs. We appreciate it if you could clarify this point.

6-2 According to Held & Ilg (2011) and de Wild-Scholten (2010), there is no data about filter cake treatment, i.e. recovery of CdTe. So, details of substance flows of Cd and Te in the plants in Perrysburg and Kulim should be clarified.

6-3 "First Solar Module Collection and Recycling Program – Frequent Asked Questions" states that 90% overall recycling rate was estimated. It should be clarified how the recycling rate was defined, and also what the other 10% consists of. In recycling of glass cullet, the contamination of impurities such as metals should be strictly minimized. So, it should be clarified how the recycling of glass cullet is achieved, i.e. for what glass cullet is used. In addition, Held & Ilg (2011) considered only heat recovery for plastic recycling. State-of-the art of plastic recycling should be reflected in LCA for PV systems.

Answers:

- SolarWorld (Si PV) and Abound Solar (CdTe PV) now have similar collection programs but First Solar was the first to introduce the program and is the only manufacturer with active recycling operations.

- Data on filter cake treatment is presented in Sinha et al. (2012).

    - There is 97% conversion of filter cake to semiconductor grade CdTe.
    - End-of-life takeback and recycling, including USM processing, accounts for ~10% of the life cycle carbon footprint and energy payback time of CdTe PV system.

- Recycling rate is recovery by mass (90% recovery of glass, 95% recovery of semiconductor)

- Other 10% for glass recycling consists of cyclon dust (mixture of glass fines and metals) that cannot be recycled.

- Recycled glass is currently used for fiberglass manufacturing

- Recycling methods are being improved to lower impurity levels to achieve float glass (solar glass) quality for closed loop glass recycling

- Semiconductor is already closed loop recycling (refined to semiconductor grade)

Report on

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

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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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Executive Summary

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 21^{st} and 22^{nd} 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].

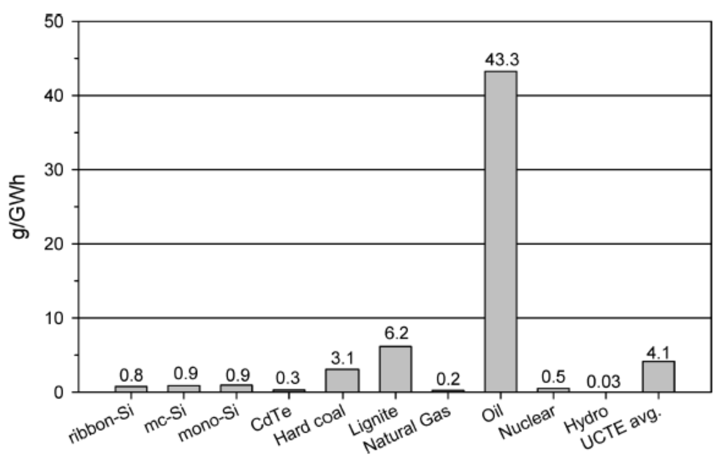

Figure 1. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption in comparison with other electricity generation options [5].

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].

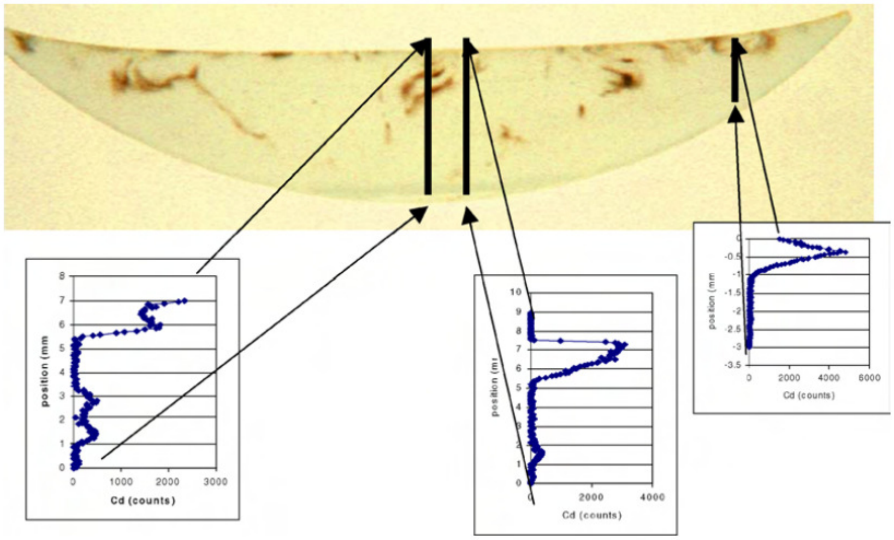

Figure 2. X-ray fluorescence microprobe analysis-vertical slice from middle of sample heated at 1100˚C; Cd counts in the center and the sides of the slice [6].

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].

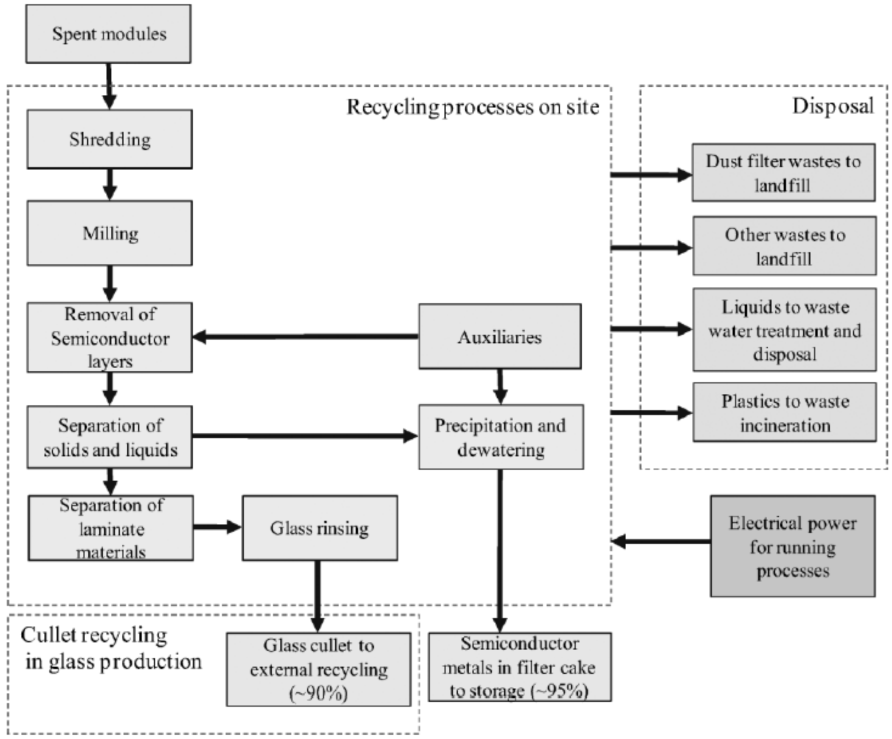

Figure 3. Flow chart of CdTe module recycling [8].

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/m²/yr	30 – 45 g CO_2eq/kWh	1.7 – 2.7 years
CdTe	Ground-mounted 0.8 PR, 1,800 kWh/m²/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^{o}C 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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Review of Environmental, Health and Safety of CdTe Photovoltaic Installations throughout Their Life-Cycle

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Abstract.

Cadmium telluride (CdTe) photovoltaic (PV) technology has recently achieved relatively high power conversion efficiency, low manufacturing cost, combined with durability, and good performance in the high temperature uses. The deployment rate of CdTe PV has grown rapidly in recent years and CdTe PV has the potential to contribute as one of the further scaling-up solar cells. This review evaluates the environmental, health and safety (EHS) of CdTe PV installations throughout their life-cycle, from raw material acquisition, module manufacturing, module use, to end-of-life disposal. The review bases the assessments on the existing scientific literatures on the EHS aspects of CdTe PV modules, including assessment of carbon footprint and energy payback time compared with other renewable energies.

1. Introduction

CdTe PV is a technology which is based on the use of a CdTe/cadmium sulfide (CdS) thin film semiconductor layer for absorption and conversion of solar energy to electricity. CdTe PV's deployment rate has grown more rapidly than conventional silicon solar technologies in recent years (Mehta, 2010). This is due to the fact that CdTe PV has recently achieved relatively high efficiency, low manufacturing cost combined with durability, and good performance in the high temperature uses (Zweibel et al., 2008).

Studies in CdTe technology started in the 1950s, when CdTe was identified as having a proper energy band gap (about 1.5 eV) which almost perfectly matched distribution of photons in the solar spectrum in terms of optimal conversion to electricity (Jenny and Bube, 1954; Goldstein, 1958). A simple heterojunction design evolved in which p-type CdTe was matched with n-type cadmium sulfide (CdS). The cell was completed by adding top and bottom contacts. Early leaders in CdTe/CdS cell efficiencies were GE in the 1960s, and then Kodak, Monosolar, Matsushita, and AMETEK. In 1999, Solar Cells Incorporated (SCI) became First Solar, which is currently a leading company in the CdTe PV market.

Life cycle assessment (LCA) involves the inventory of material and energy flows in and out of a product, and assessments of their impacts. Previous applications of LCA to PVs focused on determining energy payback time and reductions in carbon-dioxide emissions. Many reports have emphasized the need for further study on the environmental aspects of CdTe PVs, including decommissioning and recycling of end-of-life CdTe modules (Kato et al., 2001). Figure 1 shows life cycle phases of PV modules. In this review, the EHS aspects of CdTe PV systems over their entire life cycle, including extracting refining and purifying raw materials, module manufacturing, module use, and end-of-life disposal, were assessed. General parameters for the life cycle assessment, including carbon footprint and energy payback time, were also reviewed and compared with other renewable energies. Lastly, the EHS practices currently in place at First Solar, one of the leading companies in CdTe PV modules, were reviewed on the basis of a tour of First Solar's Kulim, Malaysia manufacturing and recycling plant, on May 24-25, 2012.

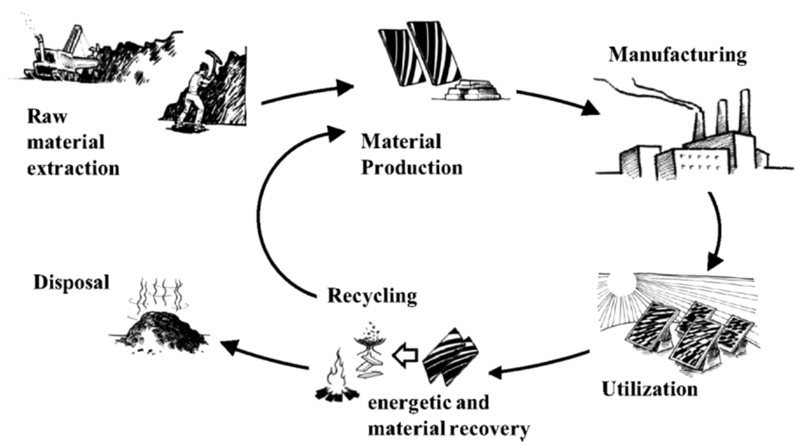

Figure 1. Life cycle phases of photovoltaic modules (Held and Ilg, 2011)

2. Lifecycle EHS Impacts of CdTe PV Systems

2.1 Production of Cd and Te

Cd is used primarily in Ni-Cd batteries and is also used in the control rods of nuclear reactors. Previously, it was used in anticorrosive plating, pigments, and stabilizers, but recently those applications were drastically curtailed. Cd is generated as a byproduct of smelting base metals, i.e., Zn ores, and to a lesser degree Pb ores and Cu ores. If it is not controlled, Cd emissions could be found in those production processes. In most recent years, conventional Zn production uses more advanced hydrometallurgy procedures that drastically reduced Cd emissions (Table 1). Nevertheless, because Zn is generated in very large quantities, more Cd is generated as byproduct than it is consumed annually. The excess can either be put to beneficial uses or be encapsulated and buried, stored for future use, or disposed of in landfills as hazardous waste. Recent study by Matsuno et al. (2012) suggested that there would be a problem due to Cd oversupply in the near future. Arguably, encapsulating cadmium as CdTe in PV modules is an important alternative to its current uses (Fthenakis, 2004; Raugei and Fthenakis, 2010).

Table 1. Cadmium emissions from old and new zinc-production processes (from Fthenakis, 2004).

Process	Cadmium emissions	
	g Cd/ton Zn	(% Cd loss)
Roast/leach/electrowinning process (hydrometallurgy)	0.2	0.008
Roast/blast furnace smelting	50	2
Former roast/blast furnace smelting (not in use any more)	100	4

One of the least understood and the most subtle concerns with CdTe PV is the supply of Te (Zweibel, 2010). Te is an element used in limited applications; outside of PV, Te is mainly used for manufacturing thermoelectric materials, machinable steel and as catalysts for producing synthetic fibers. Therefore, only a small amount of Te is available, with current annual production of approximately 640 metric tons per year (Zweibel, 2010). Most of it comes as a by-product of Cu, with smaller byproduct amounts from Pb and Au. One gigawatt (GW) of CdTe PV modules requires about 91 metric tons of Te (Zweibel, 2010), so this seems like a potentially limiting factor. From a report from International Energy Agency, thin film (CdTe and CIGS) PV market shares through mid-century are expected to be met by currently understood future tellurium and indium availability (Candelise et al., 2011). Some researchers have shown that well-known undersea ridges are rich in Te and by themselves could supply more Te than we could ever use for all of our global energy (Cohen, 1984). However, it is not yet known whether extracting this undersea Te is technically and economically feasible, nor whether there is much more tellurium elsewhere that can be recovered. Fortunately, it was reported recently that there are some sources of Te as a primary ore. Mines in Mexico, China, and Sweden have rich bismuth Te ores, with Te concentrations of almost 20% (Zweibel, 2010). These deposits will allow the economic recovery of Te, independent of the production of Cu, with minor (~1%) increase in the life cycle cumulative energy demand of CdTe PV (Fthenakis and Anctil, 2012). 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 PV modules (Fthenakis, 2012).

Some emissions could be found in the purification of byproduct Cd and Te to be semiconductor-grade Cd and Te. However, with capture techniques, i.e. high-efficiency particulate air (HEPA) filters, and waste recycling, those emissions are below acceptable levels.

2.2 CdTe Characteristics, Production, and Toxicity

CdTe is a crystalline compound with lattice constant of 0.648 nm (at 300 K), Young's modulus of 52 GPa, and poisson ratio of 0.41. Its thermal conductivity, specific heat capacity, and thermal expansion coefficient are 6.2 $W \cdot m/m^2 \cdot K$, 210 J/kg·K, and 5.9×10^{-6}/K, respectively, at 293K (Palmer, 2008). CdTe has very low solubility in water (Brookhaven National Laboratory and the U.S. Department of Energy, 2003). It can be chemically etched by using many acids, including hydrochloric and hydrobromic acid, forming (toxic) hydrogen telluride gas (Hosokawa *et al.*, 2012) and toxic cadmium salts. It is unstable in air at very high temperatures (boiling point of CdTe is about 1050˚C) (Fthenakis *et al.*, 2005). CdTe for PVs is generally produced from high-purity Cd and Te via proprietary methods. Production is limited and the volumes produced are not published. Reportedly, 100% of the feedstock is used and there are no quantifiable emissions during production of semiconductor-grade CdTe (Fthenakis, 2004).

As a cadmium compound, CdTe is often documented as toxic if ingested, if its dust is inhaled, or if it is handled improperly (i.e. without appropriate personal protective equipment and other safety precautions). Recent toxicological research by Zayed and Philippe (2009) and Kaczmar (2011) described below have differentiated CdTe from other Cd compounds. According to Held et al. (2012), the European Chemicals Agency (ECHA) no longer classified CdTe as harmful if ingested nor harmful in contact with skin. Once properly and securely captured and encapsulated, CdTe used in manufacturing processes may be rendered harmless. CdTe is less toxic than elemental Cd, at least in terms of acute exposure toxicity testing (Zayed and Philippe, 2009).

In evaluating risk from environmental emissions, toxicological data is often read-across from the parent element (Cd) to the compound (CdTe), because of limited specific toxicological data on CdTe. However, recent toxicity studies indicate that this may not be appropriate. 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 (Kaczmar, 2011).

Previously, Zayed and Philippe (2009) evaluated acute inhalation and oral toxicities of CdTe in rats and found the median lethal concentration and dose to be orders of magnitude higher than that of Cd. Moreover, prior testing by Harris *et al.* (1994) showed no detectable effects of CdTe on male or female rat reproduction.

Researchers in U.S. have reported that CdTe PV modules appear to be more environmentally friendly than all other current uses of Cd (Fthenakis, 2004). The approach to CdTe safety in EU and China is much more cautious. Cd and Cd compounds are considered as toxic carcinogens in EU, whereas China regulations previously allow some Cd products for export only (Sinha *et al.*, 2008).

For EU, the Restriction on the use of certain Hazardous Substances (RoHS) Directive is an environmental legislation that has been in effect since July 1, 2006 and has been revised in 2011. It deals with six hazardous materials in electrical and electronic equipment (including Cd). The RoHS Directive separates a product into individual parts of homogeneous materials. Each part must not contain the banned substance exceeding a maximum concentration limit. The limit is 1000 ppm (parts per million) for other five materials but only 100 ppm for Cd. In November 2010, the European Parliament, European Commission, and European Council agreed on a revised RoHS Directive (**Directive 2011/65/EU)** under which all electrical and electronic equipment (EEE) are included in the scope of the RoHS directive unless specifically excluded or exempted from coverage. PV panels are explicitly excluded from the scope of RoHS. More specifically, article 2 describes PV panels as follows; photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications (European Commission, 2011).

For China, RoHS has also been applicable recently (Design Chain Associates, 2012). The scope of Chinese RoHS includes a potential labeling and information disclosure requirement (China RoHS 1) and a materials restriction requirement applied to a separately promulgated list of electronic information products (China RoHS 2). China ROHS 2 has not yet been promulgated and is pending the publication of the China RoHS 2 catalogue. Recently some CdTe PV modules have been sold in China.

2.3 CdS and its Characteristics

CdS is an inorganic compound in a yellow solid form. As a compound that is easy to isolate and purify, it is the main source of Cd for various commercial applications (Wiberg and Holleman, 2001). CdS is mainly used as a pigment. CdS and cadmium selenide are used in manufacturing of photoresistors sensitive to visible and near infrared light. In thin-film form, CdS can be combined with other layers for use in thin-film solar cells as the *n*-type material in a *p-n* junction (Zhao *et al.*, 2009). CdS was also one of the first semiconductor materials to be used for thin-film transistors (TFTs) (Weimar, 1962).

The CdS share in the CdTe/CdS PV modules is substantially lower than the CdTe share (Beckmann and Mennenga, 2011.).CdS accounts for less than 3% of the total Cd content in the module. It has even less solubility than CdTe (< 1% solubility), low acute oral and dermal toxicity (classified as non-toxic for acute exposure in material handling requirements for shipping/transportation), and low respirable fraction (less than 10 μm) when used in PV manufacturing, which limits inhalation toxicity.

2.4 CdTe PV Manufacturing

The two leading methods of making CdTe thin films, electrodeposition of CdTe combined with chemical surface deposition of CdS (not commercially used since 2004), and high-rate vapor transport of the two compounds, use Cd compounds very efficiently. There are about 1% loss in the electrodeposition process, and about 10-30% loss in the vapor-transport process. In both processes, the Cd compounds can be collected and recycled or safely disposed of in a secure landfill (Fthenakis, 2004; Smigielski, 2011).

CdTe PV installation workers do not have the possibility of exposure to the semiconductor layer of the module because it is encapsulated between two sheets of glass. The bio-monitoring in the CdTe PV factory shows no Cd release to the workers. Moreover, the reviews of medical monitoring data in First Solar's CdTe PV manufacturing and recycling factories have concluded that the medical surveillance data for blood and urine Cd show no evidence of increased Cd exposure from the workplace. (Akbar 2009).

2.5 CdTe PV Operations

2.5.1 <u>Routine</u>

General. Under normal operation, CdTe PV modules do not pose risk to human health or the environment because the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated with a second sheet of glass. Unless the module is ground to a fine dust, particulate matters cannot be generated. The melting point of CdTe is 1041 °C, and evaporation starts at 1050 °C. Sublimation occurs at lower temperatures, but the vapor pressure of CdTe at 800 °C is only 2.5 torr (0.003 atm) (low vapor pressure). The melting point of CdS is 1750 °C and its vapor pressure due to sublimation is only 0.1 torr at 800 °C. Therefore, it is impossible for any vapors or dust to be emitted when using PV modules under normal conditions (Fthenakis, 2004).

Soil Contamination. Potential health risks from ground-mount CdTe PV installations on agricultural lands were recently evaluated by the Bavarian Agricultural Agency (Ebert and Muller, 2011). Risks from potential leaching were found to be minimal. CdTe has very low solubility in water, and it can only be chemically etched by acids, forming (toxic) hydrogen telluride gas and toxic cadmium salts as mentioned previously. Moreover, in the recycling step, it was found that highly concentrated H_2SO_4 and H_2O_2 were needed to extract Cd and Te (Fthenakis, 2004). It should also be noted that the presence of acid alone cannot etch modules. A module would have to be broken into small (mm-scale) pieces and agitated in acid (similar to the recycling process) in order to dissolve the semiconductor materials. Removal of broken modules from project sites is recommended for precautionary soil protection (Ebert and Muller, 2011). This is consistent with routine inspections and power output monitoring that are used to diagnose broken modules for collection and recycling (Sinha et al., 2012).

Solar Reflection. Diffuse reflectivity or reflecting power of a surface is generally measured by its albedo value. This value refers to a property of a material or surface defined as the total amount of energy reflected divided by the total amount of energy impacting the material or surface. Albedo value of CdTe PV modules is about 0.26 (Markvart and Castalzer, 2003; Donovan, 2010). This value is very close to the values of grass, dry grass, and uncultivated fields, indicating that the CdTe PV does not cause the problem of high solar reflection to the environment.

Table 2. Typical albedo values (Donovan, 2010).

Surface Type	Albedo
Grass	0.25
Dry grass	0.28 - 0.32
Uncultivated fields	0.26
Bare soil	0.17
Asphalt	0.15
Weathered concrete	0.20
Fresh snow	0.80 - 0.90
Water surfaces (solar angle range from 45° to 10°)	0.05 - 0.22

2.5.2 *Accidents*

Some PV stakeholders have raised concerns about the potential exposure to CdTe from non-routine circumstances, such as release during fires and leaching of broken modules.

Broken Modules. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. Fortunately, unless the CdTe PV module is ground to fine dusts recently, dust particles are not generated from PV modules. Steinberger (1997) addressed the potential of Cd leaching out by rain from broken or degraded CdTe modules. He concluded that CdTe releases are unlikely to occur during accidental breakage. The only scenario of potential exposure is if a fire consumes the PV module and releases cadmium from the material into the air. In addition, routine inspections and power output monitoring diagnose broken modules to be removed for collection and recycling (Sinha et al., 2012). A weather event that could potentially damage many modules would also significantly affect electricity production, resulting in detection and removal of broken modules through performance monitoring and inspection.

Fire. Heating experiments to simulate residential fires in glass-CdTe-glass PV modules showed that most of the Cd content was encapsulated in the molten glass matrix. The pathway for some loss of Cd was likely through the perimeter of the modules before the two sheets of glass fused together, which is a very small area. It was estimated that only <0.04% of the Cd content would be emitted during the fires that cover the wide flame temperature zone of 760-1100°C. Multiplying this with the probability of occurrence for residential fires and the probability of sustained fires in utility systems, the emissions of Cd are considered to be essentially zero (Fthenakis *et al.*, 2005).

The distribution calculations for worst-case conditions, assuming a total release of all cadmium inventories showed that a serious danger for the immediate neighborhood and general public can certainly be excluded when CdTe PV modules burn (Beckmann and Mennenga, 2011). Moreover, recent fate and transport evaluations applying conservative assumptions of cadmium exposures from rainwater leaching of broken CdTe PV modules and emissions from a fire concluded that concentrations at the point of exposure would be expected to be below published health-based screening levels (Sinha *et al.*, 2011).

Even though the possibility of sustained fires in utility systems and the Cd content emitted are very low, routine maintenance of the PV system to prevent the fire or any accident should be carried out. Not only Cd, but a tiny percentage of Te was released in the typical residential fire temperature range 760-900°C, but a significant fraction of Te was released at higher temperatures (1000-1100°C) (Fthenakis *et al.*, 2005).

Hailstorm. Strong hailstorms may destroy PV modules, thus justifying a consideration on the case of broken modules. Whether Cd can be released when a module is damaged by hail, it is important to know whether the semiconductor layer, conductors, and solders are exposed to weather conditions. In practice, water could enter through hairline cracks which are likely to develop. International Electrotechnical Commission (IEC) published a standard for the hail impact test (IEC61646, section 10.17). The PV modules which pass this test before placing on the market are secure for hailstorm. With a PV free field plant, it is unlikely to expect the same small fragment size which was used for the batch/elution tests for estimating leaching potential. The front glass of solar modules is hail tested. Moreover, even in case of the breakage of the glass, the laminate protects against pollutant emission. It should be kept in mind that the batch tests for estimating leaching potential can cause a mechanical related abrasion of the CdTe layer which is unlikely to happen in free field plants (Ebert and Muller, 2011). In addition, routine inspections and power output monitoring diagnose broken modules to be removed for collection and recycling (Sinha et al., 2012). A weather event that could potentially damage many modules would also significantly affect electricity production, resulting in detection and removal of broken modules through performance monitoring and inspection.

Flood or Water Submersion. Even though CdTe has very low solubility in water, adequate toxicological and ecotoxicological information, and data on effects of flood or water submersion of broken modules are very important. Current data includes aquatic toxicity testing performed according to OECD and USEPA test guidelines with zebrafish as the recommended test species. There were no effects (lethal or sublethal) from CdTe at aquatic saturation for zebrafish over 96 h (Kaczmar, 2011). In addition, based on long-term transformation and dissolution testing of CdTe, a 1 mg/L loading showed a concentration of 15 µg of Cd/L after 28 d, indicating low (≈1.5%) long-term solubility (Kaczmar, 2011). Note that PV project site selection includes hydrological site surveying and evaluation, which limits the potential for flooding.

2.6 CdTe PV End-of-Life

Because CdTe in PV modules is encapsulated by 2 sheets of glass, even if pieces of modules inadvertently make it to a municipal waste incinerator, cadmium will dissolve in the molten glass and would become part of the solid waste (Fthenakis, 2004). The leachability tests that are used within the EU for Waste Acceptance Criteria (WAC) testing showed that the leaching potential of the modules was small and that the modules, while not acceptable for disposal in an inert landfill, would be acceptable in other classes of landfill as non-hazardous waste (Golder Associates, 2010). Concerning leaching, there are several independent studies of CdTe modules concerning mass concentration test and standard leaching tests commonly used in the European Union that assessed that CdTe PV modules are classified as a non-hazardous waste at the end of their life (Wehrens, 2011; Steinberger, 1998).

According to Thai laws and regulations on waste management (B.E. 2548; Department of Industrial Work, 2005), solar cell modules are classified as an electronic waste (E-waste). This E-waste is in the group of HA (Hazardous Waste - Absolute entry) and HM (Hazardous Waste - Mirror entry). Therefore, end-of-life PV modules have to be analyzed in the laboratory to investigate the hazards before disposal. In addition, considering Annexes I and VIII of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, Cd-containing items are classified as a controlled waste. Hazardous wastes listed as controlled items for transboundary movement are defined in the *Notification of Ministry of Industry on List of Hazardous Substances B.E. 2546 (2003),* issued under the *Hazardous Substance Act. B.E. 2535 (1992).* Therefore, before transporting spent PV modules to the recycling site or to other countries, permission from the Pollution Control Department (PCD) should be obtained and waste management procedures should be in accordance with the Basel Convention (Pollution Control Department, 2009).

Recently, the PV industry is recycling CdTe PV modules at the end of their useful life (First Solar, 2010). Recycling is important to the long-term sustainability of the PV industry for managing large future waste volumes and recovering valuable materials (glass, copper, aluminum, semiconductor materials, back contact metals, *etc.*) for use in new PV modules and other new products. Held (2009) presented the environmental profile of recycling process of spent CdTe PV modules. It showed that the life cycle primary energy demand and carbon footprint of CdTe PV can be significantly reduced through module recycling. In addition, the recovery of Cd and Te will result in further reduction of the life cycle environmental impact of CdTe PV, in addition to providing a source of Te.

3. Emissions from Overall CdTe Life Cycles

The total Cd in CdTe PV has been evaluated on a life cycle basis (Fthenakis, 2004) and found to produce minimal environmental emissions (e.g., air emissions of 0.02-0.3 g Cd/GWh compared to 2-3.1 g Cd/GWh from coal burning power plants; for other PV systems and energy generation options, see Figure 2).

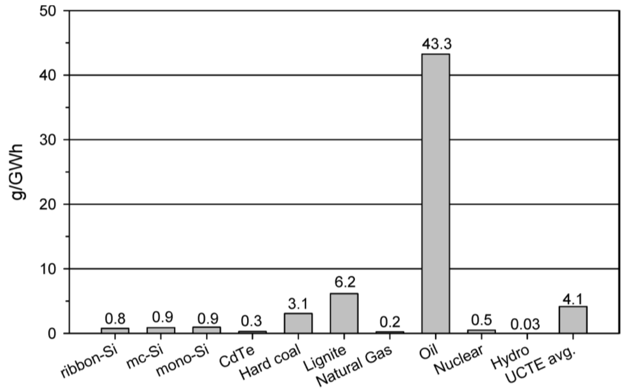

Figure 2. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumptions in comparisons with other electricity generation options (Fthenakis *et al.*, 2008).

Emissions from the life cycle of four major commercial photovoltaic technologies, *i.e.* ribbon-Si, multicrystalline Si (multi- or mc-Si), monocrystalline Si, and thin-film CdTe systems, were quantified (Fthenakis *et al.*, 2008). Replacing grid electricity with central PV systems presents significant environmental benefits, which for CdTe PV amounts to 89-98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species. In fact, life-cycle Cd emissions are even lower in CdTe PV than in crystalline Si PV, because the former use less energy in their life cycle than the latter. More specifically, thin film photovoltaics require less energy in their manufacturing than crystalline Si photovoltaics, and this translates to lower emissions of heavy metals, SO_x, NO_x, PM, and CO_2.

4. Carbon Footprint

CdTe PV provides the lowest carbon footprint of current PV technologies (de Wild-Scholten and Schottler, 2009; de Wild-Scholten, 2011) and almost lowest among other energy alternatives [*i.e.*, carbon footprints of nuclear ~8; wind ~12; CdTe PV ~15; crystalline Si (2006) ~30; poly-Si (hydropower and wafer/cell/module) ~19-34; and coal ~1070 g CO_2-eq/kWh (de Wild-Scholten and Schottler, 2009; de Wild-Scholten, 2011), see Figure 3].

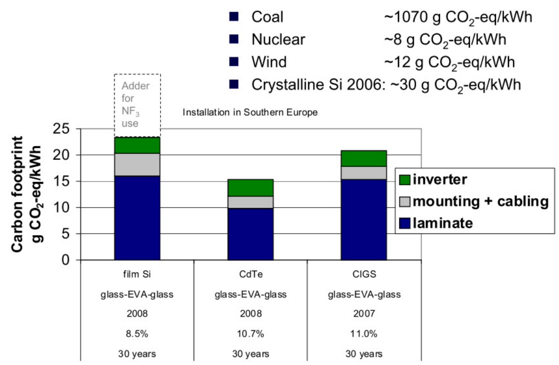

Figure 3. Carbon footprint of various PV systems compared with other electricity generation options (de Wild-Scholten and Schottler, 2009)

5. Energy Payback Time

Energy payback time (EPBT) is defined as the period required for a renewable energy system to generate the same amount of energy that was used to produce, operate, and decommission the system itself (Fthenakis et al., 2011). In order for renewable energy technologies to serve as effective alternatives to fossil fuel based energy, their EPBT must be short. Once the EPBT has passed, the renewable energy technology is a source of green energy that displaces fossil fuels.

CdTe PV provides the fastest energy payback time of current PV technologies, *i.e.*, energy payback times of CdTe PV (2010) ~0.7 years; µm-Si (2012) ~1 year; CIGS PV (2010) ~1.3 years; multicrystalline Si (2009) ~1.6 years; and monocrystalline Si (2008) ~ 1.7 years (de Wild-Scholten, 2011; see Figure 4).

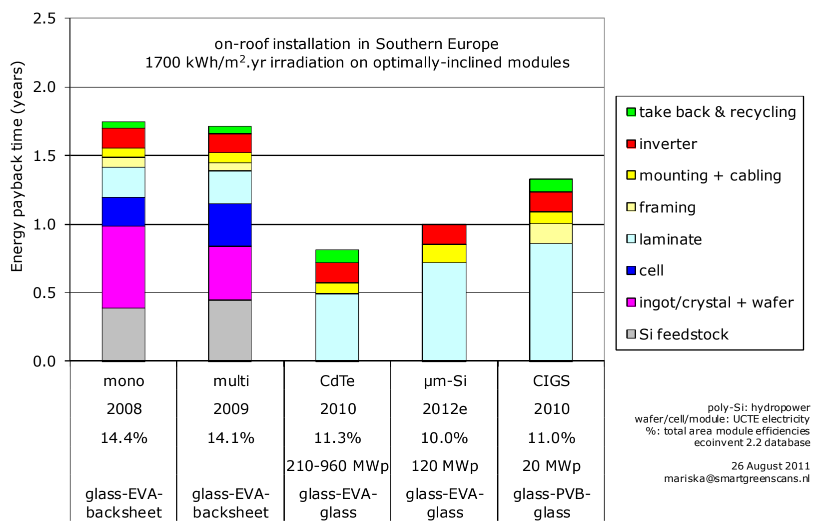

Figure 4. Energy payback time of commercial PV systems installed on roof-top at irradiation of 1700 kWh/m^2/year on optimally-inclined modules. The data for micromorphous silicon PV modules are estimates (de Wild-Scholten, 2011).

6. First Solar's CdTe PV Manufacturing and Recycling EHS Policies and Practices

According to First Solar, low cadmium emissions, small carbon footprint, and short energy payback time are primarily related to state-of-the-art technology and commitment to continuously improve the competitiveness and environmental excellence of its CdTe PV technology.

The module collection and recycling program at First Solar for end-of-life module collection and recycling, which use best available technology, provides high recovery rates for semiconductor material (95%) and glass (90%) (Held, 2009).

No major concerns were identified during this review regarding EHS aspects of First Solar's manufacturing and recycling activities. Over the course of several years, First Solar has developed EHS policies and management systems, and has demonstrated continuous improvement in these areas at its facilities globally. First Solar ensures compliance with its EHS policies and regulatory requirements not only through internal practices, but also through periodic audits by third parties. First Solar takes a proactive risk assessment-based approach to EHS issues and promotes continuous improvements to further reduce risks.

7. Conclusions and Recommendations

CdTe PV is an important thin film PV technology that has grown rapidly in recent years. CdTe PV provides the lowest carbon footprint and fastest energy payback time of current PV technologies and other energy alternatives. In the overall lifecycle of CdTe PV, it is found to produce minimal environmental emissions (e.g., air emissions of 0.02-0.3 g Cd/GWh compared to 2-3.1 g Cd/GWh from coal burning power plants) compared to other PV systems and energy generation options. Replacing grid electricity with central PV systems presents significant environmental benefits, which for CdTe PV amounts to 89-98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species.

The principal EHS concern for CdTe PV is the potential introduction of Cd or other hazardous compounds into the environment. To assess risks, CdTe PV has been evaluated on a life cycle basis with regards to raw material, manufacturing, use, and decommissioning stages with recycling.

Raw Materials

Cd and Te are generated as a byproduct of smelting base metals. Encapsulating Cd in CdTe PV modules is an alternative to its current uses in other applications. There is the potential for a Cd oversupply problem in the near future. CdTe PV systems that use cadmium as a raw material should be considered as one of the solutions for a sustainable use of cadmium. However, on another point of view, the most subtle concern of CdTe PV is the supply of Te, because Te is an element not currently used for many applications. Outside of PV, Te is only used in the manufacturing of thermoelectric materials, machinable steel, and in catalysts for producing synthetic fibers. Therefore, only a small amount of Te is available. One gigawatt of CdTe PV modules would require about 91 metric tons of Te compared with current annual production of approximately 640 metric tons per year, so this seems like a potentially limiting factor. Fortunately, recently there are some sources of Te as a primary ore. Forecasted International Energy Agency thin film PV market shares through mid-century are expected to be met by currently understood future indium and tellurium availability. 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.

Manufacturing

As a cadmium compound, CdTe is often documented as toxic if ingested, if its dust is inhaled, or if it is handled improperly. Nonetheless, the European Chemicals Agency (ECHA) does not classify CdTe as harmful if ingested nor harmful in contact with skin. With proper EHS practices in PV manufacturing, there is no sign of health risk found in CdTe PV workers.

Use

For CdTe PV modules, under normal operation, the modules do not pose a risk to human health or the environment because the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated with a second sheet of glass. Acids can cause etching of the modules; however, it should be noted that a module would have to broken into small (mm-scale) pieces and agitated in acid (similar to the recycling process) in order to dissolve the semiconductor material. Removal of broken modules from project sites is recommended for precautionary soil protection. This is consistent with routine inspections and power output monitoring that are used to diagnose broken modules for collection and recycling.

In foreseeable accidents, e.g. fire, breakage of CdTe PV modules, the emissions of Cd or Cd compounds have been proven to be negligibly small, because the Cd content would be encapsulated in the molten glass matrix in case of fire, and because of the low solubility of CdTe in case of breakage. The pathway for some Cd loss is likely through the perimeter of the modules before the two sheets of glass fused together, which is a limited area. It is estimated that only <0.04% of the Cd content would be emitted during the fires.

Decommissioning

After uses, CdTe PV modules are classified as a non-hazardous waste in the European Union and as hazardous waste in Thailand. The recycling of CdTe PV modules at the end of their useful life provides high recovery rates for semiconductor material (95%) and glass (90%).

Recommendations

In our opinion, CdTe PV systems are well suited for use in large-scale operations, like solar farms with adequate monitoring and environmental management systems, which can provide significant environmental benefits for reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species. As power systems in general should not be located in high risk areas, CdTe PV systems should not be located close to potentially hazardous facilities to avoid potential risks under extreme conditions or in the events of disaster.

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Summary of an Environmental, Health and Safety Impact Evaluation of CdTe PV Installations Throughout Their Life-cycle

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Worldwide spread environmental concerns about the level of greenhouse gas (GHG) emission and its cumulative effect on global climate change, together with a steady increase of fossil fuel prices have triggered a strong demand for truly innovative electric generation technology. Availability of renewable energy sources that are also affordable can effectively help to cut down global fossil fuel demand, GHG emissions and other pollutants deriving from fossil fuel combustion.

PV electricity is among the most promising forms of renewable energy. It is very flexible because it can operate in a wide range of environments. Moreover, PV energy generation can rely on technologies that in the last few years have shown remarkable progress in terms of conversion efficiency and life-cycle environmental performance. At the same time the production capacity of the PV industry has grown considerably. A larger scale production decreases energy consumption for manufacturing and increases yields. Cadmium Telluride (CdTe) thin film PV technology has grown at a faster rate than conventional SI technology and First Solar the world's leading CdTe PV manufacturer has reached an annual production capacity of over 2.2 GWp in 2011.

A major recent advance of PV technology toward an even higher level of sustainability was the introduction of an end-of-life take back and recycling program. First Solar was the first PV company to introduce this kind of program in 2005. Over 200 PV companies have followed suit and became Full Compliant Members of PV CYCLE, the voluntary industry association focused on the take-back and recycling of end-of-life PV modules.

By replacing fossil fuel combustion with PV to generate electricity we can cut down the emission of greenhouse gas and of several other pollutants that threaten the environment and human health such as NO_x, SO_2, particulate and heavy metals. The importance of CdTe PV in promoting PV power generation relies on cost effectiveness. In fact, CdTe PV combines durability, high efficiency and performance in high temperature conditions with a low manufacturing cost. Thanks to these features, CdTe PV technology provides the lowest energy payback time and the lowest carbon footprint of all PV technologies available. Lowest energy payback time means that CdTe PV is the fastest to return by solar energy the amount of energy required over its entire production and end-of-life management cycle. With the lowest energy payback time and carbon footprint the CdTe PV industry can also sustain faster growth rates and still retain a positive environmental impact profile. According to evaluations by independent scientific authorities replacing European or US grid electricity with CdTe PV power plants amounts to 89-98% reduction of greenhouse gas emission, pollutants and heavy metals including Cadmium[1].

CdTe PV is also a safe technology. The active thin film semiconductor layer is a junction between Cadmium Sulphide (CdS) and CdTe. CdS content is only about 3% of the total, which is why this PV technology is named after CdTe. CdTe and CdS are very stable semiconducting compounds. CdS is more stable than Cd and CdTe is more stable than both its constituents, that are cadmium (Cd) and tellurium (Te) and of many other parent compounds. The CdS/CdTe layer thickness in PV panels is only a few (less than half a human hair). The thin CdS/CdTe film is permanently bound to its glass substrate thanks to the use of an advanced vapor deposition technique and finally it is sandwiched by another layer of glass. This double glass encapsulation structure prevents any exposure of the semiconductor film to atmospheric agents and protects it from accidental damage. Thanks to physical and chemical stability of the CdS and CdTe semiconductors and thanks to the advanced manufacturing technology, the CdTe PV module under normal operation is virtually a zero Cd emission source.

Fossil fuels are a storage place for the highly toxic Cd that is released in air when the fuel is combusted. Normally operating PV panels are zero Cd emission sources. Thus direct Cd release from CdTe PV panels, if any, may occur in principle via the processing and transformation steps involved in the manufacturing and end-of-life stages (disposal or recycling) of the PV modules. The scientific community scrutinized the potential release of Cd by CdTe PV modules through the entire life-cycle: from the sources of raw materials, through CdTe PV modules manufacturing, normal operation and until management of CdTe PV end-of-life modules. The result of this research is that direct emission of Cd through the life-cycle of CdTe PV modules is negligible. The only measurable Cd emission that can be attributed to CdTe PV is due to the combustion of fossil fuels used to generate the electricity required by manufacturing (and recycling) process[2]. For every GWh of electric energy produced the Life-cycle-Cd release of CdTe PV is over one hundred times smaller than Cd air emission from a fossil fuel power plant[1]. Moreover CdTe is the PV

[1] Fthenakis, et al. Emissions from Photovoltaic Life Cycles, Environmental Science and Technology, 2008, Vol. 42, 2168-2174.

[2] Fthenakis, V.M., Life Cycle Impact Analysis of Cadmium in CdTe PV Production, Renewable & Sustainable Energy Reviews, 2004, Vol. 8, 303-334.

technology requiring the smallest amount of energy for its manufacturing cycle, which means that CdTe PV is also the weakest Cd emitter of all the PV technologies available.

An important issue related to the promotion of large-scale PV facilities is the compatibility of PV and agriculture. Several PV mounting solutions are under study to allow agricultural activity at the site of PV plants. PV power plants based on CdTe PV modules technology are safe and compatible with agriculture. Combining PV electricity production with agriculture can be very beneficial for both activities.

CdTe PV modules produced by First Solar were certified as non hazardous waste,[3] that means suitable for landfill disposal. However, take back and recycling is seen, both by experts and by the environmentally concerned public, as one of the routes to improve the green footprint of all PV companies. It promotes producer responsibility and optimization of PV design to match recycling procedures. Take back and recycling is also a potential way to recover materials and try to reduce the cumulative energy demand and associated carbon footprint of PV modules. Availability of end-of-life PV panels is currently low due to the young age of most PV installations compared to their project life-time. However, in about ten years time, the possibility, but also the demand for recycling is expected to become substantial. It was estimated that PV waste in Germany by 2020 will amount to35,000 tons.

The take back and recycling program offered by First Solar is applied to every module produced. The cost of take back and recycling is included in the cost of the CdTe PV module and the money allocated to this part of the process is managed by an independent trust fund. The environmental impact of the recycling process at First Solar was evaluated by independent researchers[4] and it was found that the whole process allows the recovery of about 90% of glass and 95% of valuable CdTe. Glass recycling is very effective to reduce greenhouse gas emissions. It turns out that melting pure glass reduces these emissions by 30%, compared to melting raw glass material that typically has higher melting point and a high carbon impurity content that burns in the melting process.

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Summary Report
Environmental, Health, and Safety (EHS) Aspects of
First Solar Cadmium Telluride (CdTe) Photovoltaic (PV) Systems
6-7 July 2009

Daniel Lincot, Coordinator
Directeur de recherche au CNRS

Experts: Daniel Lincot (CNRS), Rodolphe Gaucher (INERIS), Erik Alsema (Utrecht University), Alain Million (CEA), Arnulf Jäger-Waldau (European Commission JRC)

Carried out under the authority of the French
Ministry of Ecology, Energy, Sustainable Development, and the Sea

This review was carried out under the authority of the French Minister of Ecology, Energy, Sustainable Development, and the Sea, following the request of First Solar and EDF Energies Nouvelles with the aim of conducting an independent and complete evaluation of the environmental, health, and safety (EHS) aspects of First Solar's cadmium telluride (CdTe) photovoltaic (PV) systems. The review was designed to assess these aspects using life cycle analysis, taking into account manufacturing, product use, and end-of-life recycling and disposal of the systems. Five experts were selected from France's Centre National de la Recherche Scientifique (CNRS), the University of Utrecht, France's Institut National de l'Environnement Industriel et des Risques (INERIS), France's Commissariat à l'Énergie Atomique (CEA), and the European Commission Joint Research Centre. None of the experts has a direct interest in First Solar. The panelists are specialists in life cycle analysis, EHS practices and regulation, CdTe materials research, and photovoltaics. The review was led by Dr. Daniel Lincot of CNRS.

The expert panel based its assessment on the available third-party literature on CdTe and CdTe PV and internal First Solar documents. In addition, the experts conducted a visit of First Solar's manufacturing and recycling facilities in Germany and met with key plant staff and company management. This allowed in-depth analysis of key technical EHS aspects of the manufacturing, waste management, and recycling processes in place at First Solar.

This review follows up on a similar 2005 peer review, which was organized by the European Commission's Joint Research Centre (JRC) and moderated by the German Federal Ministry of Environment (BMU). The expert panel reviewed the findings of that review as well as updates and changes since that review took place.

The following are the panel's conclusions based on its full in-depth report:

- During standard operation of CdTe PV systems, there are no cadmium emissions – to air, to water, or to soil. In the exceptional case of accidental fires or broken panels, scientific studies show that cadmium emissions remain negligible. Accordingly, large-scale deployment of CdTe PV can be considered safe to human health and the environment.

- The carbon footprint of First Solar's CdTe PV systems is the lowest among currently available PV technologies, and compares well with nuclear and wind technologies. CdTe PV can contribute decisively to the objective of a rapid reduction of CO_2 emissions in order to combat climate change.

- The energy payback time of First Solar's CdTe PV systems is less than one year, which is the shortest among all currently available PV technologies.

- Atmospheric life cycle emissions of cadmium from CdTe PV are very low; liquid waste emissions are well below regulations for wastewater effluents and progress continues to be made to reduce this level.

- First Solar's low cadmium emissions, small carbon footprint, and short energy payback time are primarily related to First Solar's state-of-the-art technology and commitment to continuously improving the competitiveness and environmental excellence of its CdTe PV technology.

- First Solar's pre-funded program for end-of-life panel collection and recycling, which uses best available technology, resolves concerns about cadmium recovery from spent panels.

With respect to First Solar's EHS aspects, the expert panel found that:

- No major concerns were identified during this review regarding EHS aspects of First Solar's manufacturing and recycling activities. Over the course of several years, First Solar has developed EHS policies and management systems, and has demonstrated continuous improvement in these areas at its facilities globally. First Solar ensures compliance with its EHS policies and regulatory requirements not only through internal practices, but also through periodic audits by third parties.

- First Solar has successfully obtained ISO 14001 certification of its environmental management systems for its plants in Germany and the United States, and is on track to obtain certification for its Malaysian facility by the end of 2009.

- First Solar has a true commitment to EHS risk prevention, taking a long-term perspective.

- First Solar takes a proactive risk assessment-based approach to EHS issues and promotes continuous improvements to further reduce risks.

- First Solar has implemented several important EHS management programs, including specific cadmium management programs.

- Data from First Solar's Frankfurt (Oder) manufacturing facility on workplace and health monitoring, as well as on emissions to the environment, presented during the review show that First Solar's emissions are low compared to legal, recommended, and internal limit values. In fact, they are in many cases more than one order of magnitude lower than the limit value.

- First Solar samples with high frequency the exposure of its employees to cadmium compounds (by both workplace air quality monitoring and medical monitoring). Over its entire ten-year monitoring history, the company and its third-party auditors have detected no evidence of cadmium exposure among its employees.

In conclusion, CdTe PV, as developed by First Solar, is the leading PV technology in terms of carbon footprint and energy payback time, and at the same time has the lowest manufacturing cost per watt of all PV technologies. During normal operation – as well as in the case of fire or broken panels – risks are negligible, and so the large-scale deployment of CdTe PV can be considered safe to human health and the environment. First Solar's CdTe PV represents an important breakthrough in renewable energy technologies towards large-scale applications, contributes decisively to the much-needed acceleration of PV deployment, and has an excellent environmental profile. With respect to manufacturing operations, First Solar has policies, practices, and management systems in place to protect the health and safety of its workers. It also has policies, practices, and management systems in place to protect the environment where its manufacturing and recycling operations are located and continuously seeks further improvements.

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Conference Paper

CdTe PV: Real and Perceived EHS Risks

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CdTe PV: Real and Perceived EHS Risks

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ABSTRACT

As CdTe photovoltaics reached commercialization, questions were raised about potential cadmium emissions from CdTe PV modules. Some have attacked the CdTe PV technology as unavoidably polluting the environment, and made comparisons of hypothetical emissions from PV modules to cadmium emissions from coal-fired power plants. This paper gives an overview of the technical issues pertinent to these questions and further explores the potential of environmental, health, and safety (EHS) risks during production, use, and decommissioning of CdTe PV modules. The following issues are discussed: (a) the physical and toxicological properties of CdTe, (b) comparisons of Cd use in CdTe PV with its use in other technologies and products, and (c) the possibility of CdTe releases from PV modules.

1. Toxicology of CdTe

Elemental cadmium, which forms CdTe when reacted with tellurium (Te), is a lung carcinogen, and long-term exposures can cause detrimental effects on kidney and bone. Very limited data exist on CdTe toxicology, and no comparisons with the element Cd have been made [1]. However, CdTe is a more stable and less soluble compound than Cd and, therefore, is probably less toxic than Cd. However, OSHA groups all Cd compounds together, and as a general guidance, all facilities working with any such compounds should control the indoor concentrations of CdTe dust or fumes to below the Permissible Exposure Level-Time Weighted Average (PEL-TWA) Cd concentration of 0.005 mg/m^3.

The U.S. CdTe PV industry is vigilant in preventing health risks and has established proactive programs in industrial hygiene and environmental control. Workers' exposure to cadmium compounds in PV manufacturing facilities is controlled by rigorous industrial hygiene practices and is monitored by frequent medical tests. Results of years of biomonitoring have shown that there are no significant observed increases in levels of worker exposure [2].

2. Amount of Cd Compounds Encapsulated in CdTe Modules and NiCd Batteries

The amount of Cd compounds in PV modules is proportional to the area of the module and the thickness of the CdTe and CdS layers. Most CdTe layers are about 1-3 microns thick, and most CdS layers are about 0.2 microns thick. Therefore, about 3–9 g/m^2 Cd is contained in CdTe, and less than 1 g/m^2 is contained in CdS. A reasonable average amount would be about 7 g/m^2 Cd in CdTe modules. Layer thickness is expected to be reduced as research and development efforts continue, further reducing the amount of Cd compounds in the cells [3].

A CdTe module of 10% sunlight-to-electricity conversion efficiency produces about 100 W of output under standard sunlight conditions. So, there is an average of 7 g/100 W = 70 g per kW of electric power produced. In an average solar location in the United States, such as Kansas, a one-square-meter, 10%-efficient CdTe module containing 7 g of Cd would produce about 5400 kWh over its expected service life of 30 years. That is about 770 kWh per gram of Cd, or 0.001 g/kWh. (Note, this amount is in the module and is not an emission. It can be completely recycled.)

Table 1 shows a comparison of the Cd content in CdTe PV and in NiCd batteries. CdTe modules occupying 1 m^2 contain less Cd than one C–size flashlight battery. A 1-kW system would contain as much Cd as seven C-size batteries. On a per kWh basis, assuming that a NiCd battery can be recharged 700 to 1200 times over its life [4], it would produce an average of 0.046 kWh per g of its weight, which corresponds to 0.306 kWh per g of Cd contained in the battery. This is 2,500 times less than a CdTe PV module. Thus the value of using Cd in PV is much greater than its value elsewhere in the marketplace.

Table 1. Cd Content in CdTe PV and NiCd Batteries

	g/unit	g/kW (ton/GW)	mg/kWh (kg/GWh)
PV CdTe	7 g/m2	70	1.3
NiCd battery -C size	10		3265.

3. EHS Risks during Cadmium Mining

CdTe is manufactured from pure Cd and Te, both of which are by-products of smelting prime metals (e.g., Cu, Zn, Pb, and Au). About 80% of the world's production of cadmium is generated as a by-product of smelting zinc ores. Its major feedstock, sphalerite (ZnS), contains about 0.25% Cd. Secondary cadmium is produced from recycling spent NiCd batteries and other scrap. The demand of zinc has been steadily increasing for decades as driven by economic growth. Therefore, cadmium (in impure form) is produced regardless of its use. Cadmium is used primarily (~65%) in nickel-cadmium rechargeable batteries, paint pigments (~17%), plastic stabilizers (~10%), metal plating (~5%), and metal solders (~2%). When there is no cost-effective market for the metal, raw Cd is disposed of [5].

The total Cd use in the United States was 2,600 tons in 1997; globally, the total use is 19,000 to 20,000 tons. Using only 3% of the U.S. consumption of cadmium (i.e., 78 tons) in the manufacture of CdTe solar cells would generate over 1 GW of new PV per year. Note that the total current PV capacity in the United States is only 0.3 GW and is projected to grow (under optimistic assumptions) to about 3.2 GW/yr by 2020. Even if we envision PV production that is an order of magnitude higher, it would require only about a third of the current U.S. Cd consumption. Yet to change the world's energy infrastructure with CdTe PV, much less Cd would be needed, and it would not impact the overall smelting of Cd at all. In fact, it would provide a beneficial use of Cd that could otherwise be cemented or end up in a waste dump.

4. EHS Risks in CdTe PV Manufacture

In production facilities, workers may be exposed to Cd compounds through the air if contaminated, and by ingestion from hand-to-mouth contact. Inhalation is probably the most important pathway, because of the larger potential for exposure and higher absorption efficiency of Cd compounds through the lung than through the gastrointestinal tract. Processes in which Cd compounds are used or produced in the form of fine particulates or vapor present larger hazards to health. Hazards to workers may arise from feedstock preparation, fume/vapor leaks, etching of excess materials from panels, maintenance operations (e.g., scraping and cleaning), and during waste handling. Caution must be exercised when working with this material, and several layers of control must be implemented to prevent exposure of the employees. In general, the hierarchy of controls includes engineering controls, personal protective equipment, and work practices. The U.S. industry is vigilant in preventing health risks, and has established proactive programs in industrial hygiene and environmental control. Workers' exposure to cadmium in PV manufacturing facilities is controlled by rigorous industrial hygiene practices and is continuously monitored by medical tests, thus preventing health risks [2].

5. Can CdTe from PV Modules Harm Our Health or the Environment?

Toxic compounds cannot cause any adverse health effects unless they enter the human body in harmful doses. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. The thin CdTe/CdS layers are stable and solid and are encapsulated between thick layers of glass. Unless the module is purposely ground to a fine dust, dust particles cannot be generated. The vapor pressure of CdTe at ambient conditions is zero. Therefore, it is impossible for any vapors or dust to be generated when using PV modules.

The only issue of some concern is the disposal of the well-encapsulated, relatively immobile CdTe at the end of the modules' useful life. Thin CdTe PV end-of-life or broken modules pass Federal (TCLP-RCRA) leaching criteria for non-hazardous waste [6]. Therefore, according to current laws, such modules could be disposed of in landfills. However, recycling PV modules offers an important marketing advantage, and the industry is considering it as they move toward large and cost-effective production [7,8]. This issue of recycling is not unique to CdTe. The disposal of current x-Si modules, most of which incorporate Pb-based solder, presents similar concerns. Recycling the modules at the end of their useful life completely resolves any environmental concerns.

6. Do CdTe Modules Present Additional Health Risks during a Fire?

The flame temperatures in typical U.S. residential fires are not high enough to vaporize CdTe; flame temperatures in roof fires are in the 800^{o}–900^{o}C range, and, in basement rooms, in the 900^{o}–1000^{o}C range [9]. The melting point of CdTe is 1041^{o}C, and evaporation starts at 1050 ^{o}C. Sublimation occurs at lower temperatures, but the vapor pressure of CdTe at 800 ^{o}C is only 2.5 torr (0.003 atm). The melting point of CdS is 1750^{o}C, and its vapor pressure due to sublimation is only 0.1 torr at 800^{o}C. Preliminary studies at Brookhaven [10] and at the GSF Institute of Chemical Ecology in Germany [11] showed that CdTe releases are unlikely to occur during residential fires or during accidental breakage. The thin layers of CdTe and CdS are sandwiched between glass plates; at typical flame temperatures (800^{o}–1000°C), these compounds would be encapsulated inside the molten glass so that any Cd vapor emissions would be unlikely. In any case, the fire itself and other sources of emissions within the burning structure are expected to pose an incomparably greater hazard than any potential Cd emissions from PV systems.

7. CdTe PV Can Prevent Cd Emissions from Coal-Burning Power Plants

Coal-burning routinely generates Cd, because Cd is contained in the coal. A typical U.S. coal-power plant will generate waste in the form of fine dust or cake, containing about 140 g of Cd, for every GWh of electricity produced. In addition, a minimum of 2 g of Cd will be emitted from the stack (for plants with perfectly maintained electrostatic precipitators or bag-houses operating at 98.6% efficiency, and median concentration of Cd in U.S. coal of 0.5 ppm) [12]. Power plants with less efficient pollution controls will produce more Cd in gaseous form. Furthermore, a typical U.S. coal-power plant emits about 1000 tons of CO_2, 8 tons of SO_2, 3 tons of NOx, and 0.4 tons of particulates per GWh of electricity produced. All these emissions will be avoided when PV replaces coal-burning for some fraction of electricity generation.

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8. Conclusion

The potential EHS risks related to the cadmium content of CdTe PV modules were highlighted for all the different phases of a large-scale implementation of the technology. The basic conclusions are:

Cd Mining: Cadmium is produced primarily as a by-product of zinc production. Because Zn is produced in large quantities, substantial quantities of cadmium is generated as a by-product, no matter how much Cd is used in PV, and can either be put to *beneficial* uses or *discharged* into the environment. When the market does not absorb the Cd generated by metal smelters/refiners, it is cemented and buried, stored for future use, or disposed of to landfills as hazardous waste. Arguably, encapsulating cadmium as CdTe in PV modules presents a safer use than its current uses and is much preferred to disposing it off.

CdTe PV Manufacture: In CdTe PV production facilities, workers may be exposed to Cd compounds through the air they breathe and by ingestion from hand-to-mouth contact. These are real risks and continuing vigilance is required. However, current industrial practice suggests that these risks can be managed and controlled successfully.

CdTe PV Use: No emissions of any kind can be generated when using PV modules under normal conditions. Any comparisons made with cadmium emissions from coal fired power plants are erroneous, because they compare potential accidental emissions from PV systems to routine (unavoidable) emissions from modern coal-fired plants. In reality, PV, when it replaces coal-burning for electricity generation, will prevent Cd emissions in addition to preventing large quantities of CO_2, SO_2, NOx, and particulate emissions.

Related to NiCd batteries, a CdTe PV module uses Cd about 2500 times more efficiently in producing electricity. A 1-kW CdTe PV system contains as little cadmium as seven size-C NiCd batteries. Thus the incremental risk to the house occupants or firefighters from roof fires is negligible. In addition, it is unlikely that CdTe will vaporize during residential fires because the flames are not hot enough. In any case, the fire itself would pose a much greater hazard than any potential Cd emissions from PV systems.

CdTe PV Decommissioning: The only environmental issue is what to do with the modules about 30 years later, if they are no longer useful. Although cadmium telluride is encapsulated between sheets of glass and is unlikely to leach out, the PV industry is considering recycling of these modules at the end of their useful life. Recycling will completely resolve any environmental concerns.

In conclusion, the environmental risks from CdTe PV are minimal. Every energy source or product may present some environmental, health, and safety hazards, and those of CdTe are by no means barriers to scaling-up the technology.

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As CdTe photovoltaics reached commercialization, questions have been raised about potential cadmium emissions from CdTe PV modules. Some have attacked the CdTe PV technology as unavoidably polluting the environment, and made comparisons of hypothetical emissions from PV modules to cadmium emissions from coal fired power plants. This paper gives an overview of the technical issues pertinent to these questions and further explores the potential of EHS risks during production, use and decommissioning of CdTe PV modules. The following issues are discussed: (a) The physical and toxicological properties of CdTe, (b) comparisons of Cd use in CdTe PV with its use in other technologies and products, and the (c) the possibility of CdTe releases from PV modules.

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