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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
Dr. Hiroki Hondo, Prof., Yokohama National University, Japan

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].

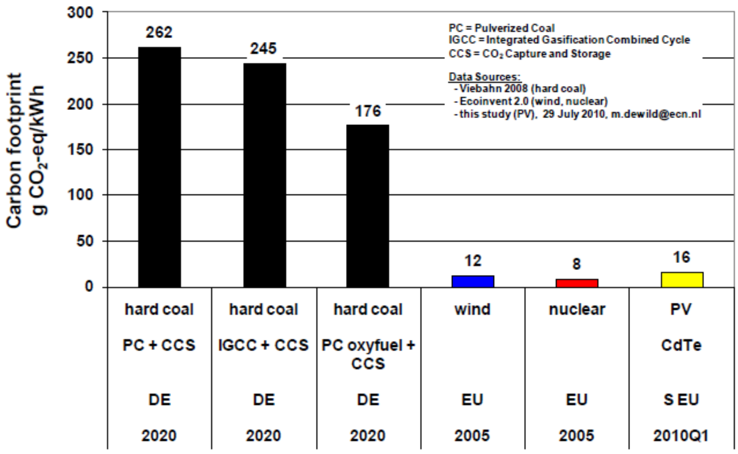

Fig. 1. From de Wild-Scholten (2010) [12]

· 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].

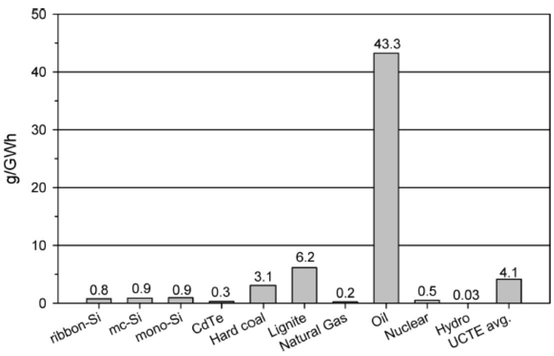

FIGURE 3. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 yrs. Ground-mounted BOS (*18*) is assumed for all PV systems; comparisons with other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

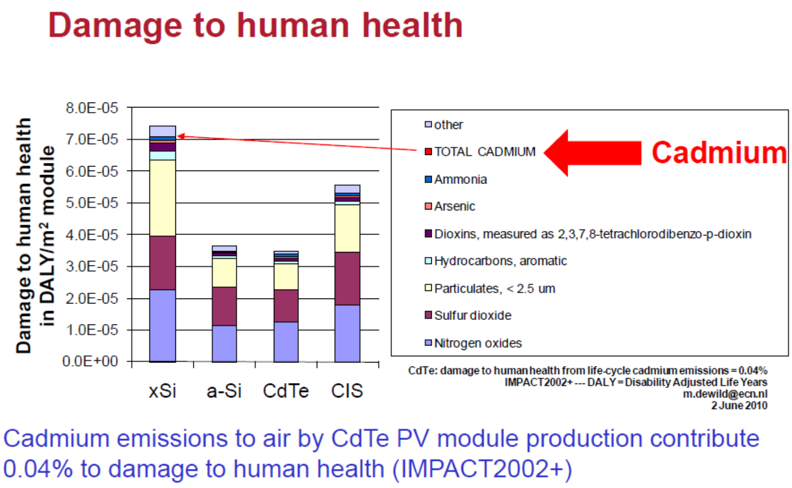

Fig. 3. From de Wild-Scholten (2010) [12]

· 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].

Scientific Documents

EHS Risks

1) Beckmann, J., and Mennenga, A., 2011. Calculation of emissions when there is a fire in a photovoltaic system made of cadmium telluride modules. Bavarian Environmental Agency, Augsberg, Germany.

2) Fthenakis, V.M., Fuhrmann, M., Heiser, J., Lanzirotti, A., Fitts, J., and Wang, W. 2005. "Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires," Progress in Photovoltaics: Research and Applications, 13 (8): 713-723.

3) Golder Associates, Review and Comments on Reports by NGI: Environmental Risks Regarding the Use and Final Disposal of CdTe PV Modules and Leaching from CdTe PV Module Material – Results from Batch, Column and Availability Tests, May 2010.

4) Harris, et al., The General and Reproductive Toxicity of the Photovoltaic Material Cadmium Telluride (CdTe), Toxicologist, 14 (1): 267, March 1994 (abstract).

5) Kaczmar, S., Evaluating the Read-Across Approach on CdTe Toxicity for CdTe Photovoltaics, SETAC North America 32nd Annual Meeting, Boston, November 2011.

6) Sinha, P., Balas, R., and Krueger, L., Fate and Transport Evaluation of Potential Leaching and Fire Risks from CdTe PV, 2011, 37th IEEE Photovoltaic Specialists Conference, Seattle, WA

7) Smigielski, K. 2011. Fundamentals & EHS Challenges of PV Manufacturing. SESHA/SIA Joint Symposium, Scottsdale, AZ, May 16-20.

8) Wehrens., S. 2011. Certificate of End-of-Life Waste Characterization. GFBU Consult, Hoppegarten, Germany.

9) Zayed, J., and Philippe, S., "Acute Oral and Inhalation Toxicities in Rats with Cadmium Telluride," International Journal of Toxicology, 28 (4): 259-265, 2009.

10) Sinha, P., Balas, R., Krueger, L., and A. Wade. 2012. Fate and Transport Evaluation of Potential Leaching Risks from Cadmium Telluride Photovoltaics. *Environmental Toxicology and Chemistry*, in press.

11) Sinha, P., M. Cossette, and J.-F. Ménard. 2012. End-of-Life CdTe PV Recycling with Semiconductor Refining. To be presented at 27th EU PVSEC, Frankfurt, Germany, September 24-28.

Life Cycle Impacts

12) de Wild-Scholten, M., Energy payback and carbon footprint of PV technologies, presented at 20th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes, Breckenridge, USA, August 2010.

13) de Wild-Scholten, M., and Schottler, M., Solar as an Environmental Product: Thin-film Modules – Production Processes and their Environmental Assessment, Energy Research Center at the Netherlands and M+W Zander, April 2009.

14) Fthenakis V.M., "Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production," Renewable and Sustainable Energy Reviews, 8, 303-334, 2004.

15) Fthenakis, V.M., Kim H.C., and Alsema, E., "Emissions from Photovoltaic Life Cycles," Environmental Science and Technology, 42, 6 (2008).

16) Fthenakis, V. and H. C. Kim. 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews, 13: 1465–1474.

17) Held, M., Life Cycle Assessment of CdTe Module Recycling, 24th EU PVSEC Conference, Hamburg, Germany, 2009.

18) Held, M., and Ilg, R., Update of Environmental Indicators and Energy Payback Time of CdTe Photovoltaic Systems in Europe, Progress in Photovoltaics: Research and Applications, 2011, Vol. 19, 614-626.

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

20) 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.

21) de Wild-Scholten, M. Environmental Profile of PV Mass Production Globalization,

presented at the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg Germany, September 2011.

Other Studies

22) Matsuno, Y., Hur, T., and V. Fthenakis, Dynamic modeling of cadmium substance flow with zinc and steel demand in Japan, *Resources, Conservation and Recycling*, 61 (2012) 83– 90.

First Solar Documents

23) First Solar, First Solar FS Series 3 PV Module, 2010.

24) First Solar, Collection and Recycling Video, (available at http://www.firstsolar.com/Sustainability/Environmental/Module-Collection-and-Recycling-Program)

25) First Solar, Module Collection and Recycling Program, Frequently Asked Questions. 2010

26) First Solar, Summary: Module Collection and Recycling Program. 2009.

Other Reports (including non-public documents)

27) County of San Luis Obispo, Final Environmental Impact Report for the Topaz Solar Farm Project, Department of Planning and Building.

28) Brouwers, T. 2010a. Bio-elution test on cadmium telluride. ECTX Consult, Liège, Belgium.

29) Agh, 2011. Acute toxicity test with cadmium telluride on zebrafish. Lab Research Ltd, Veszprém, Hungary

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)