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.

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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.

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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]:

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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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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' (presented at 50iest Annual Meeting of the Society of Toxicology, Washington D.C., USA, 2011)

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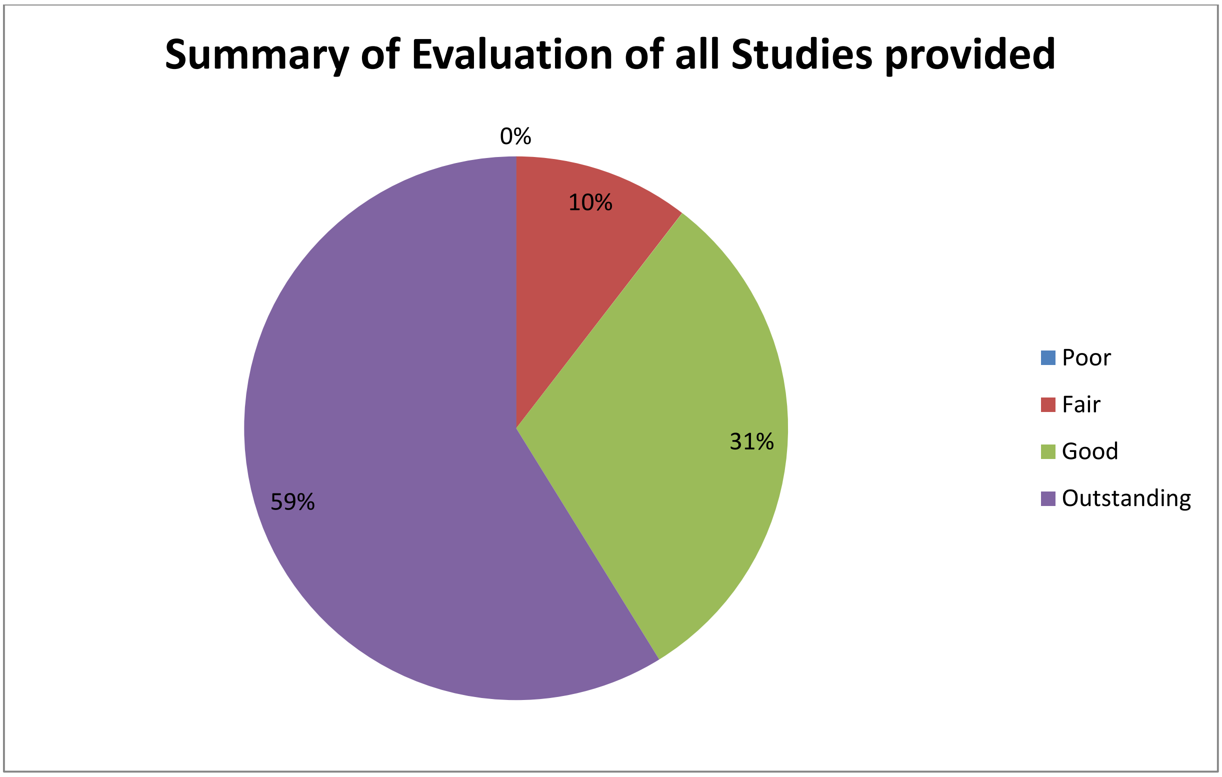
Appendix 1. Summary of evaluation of scientific journal articles

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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