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.

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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 9.5×10^{-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.

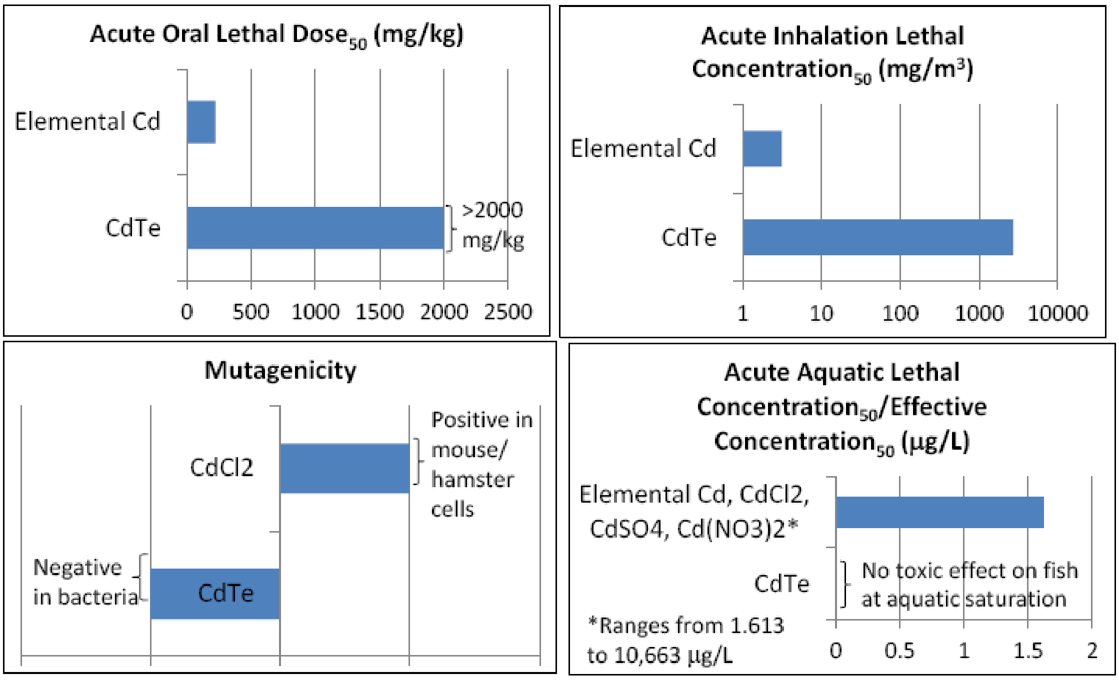


Figure 1 Comparative toxicity between Cd and CdTe[10]

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.

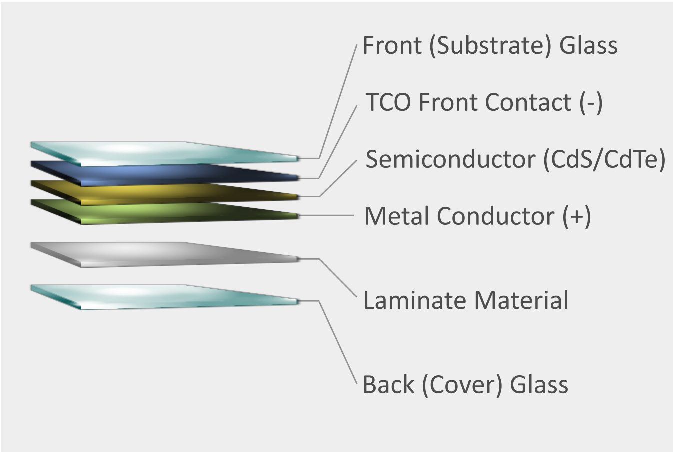


Figure 2 Schematic representation of First Solar module architecture[12]

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

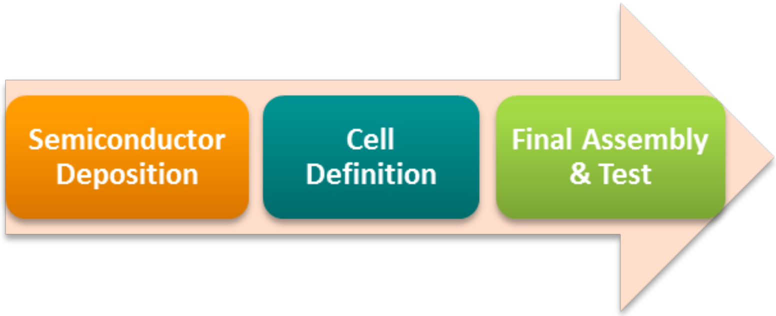


Figure 3 First Solar's manufacturing process

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.

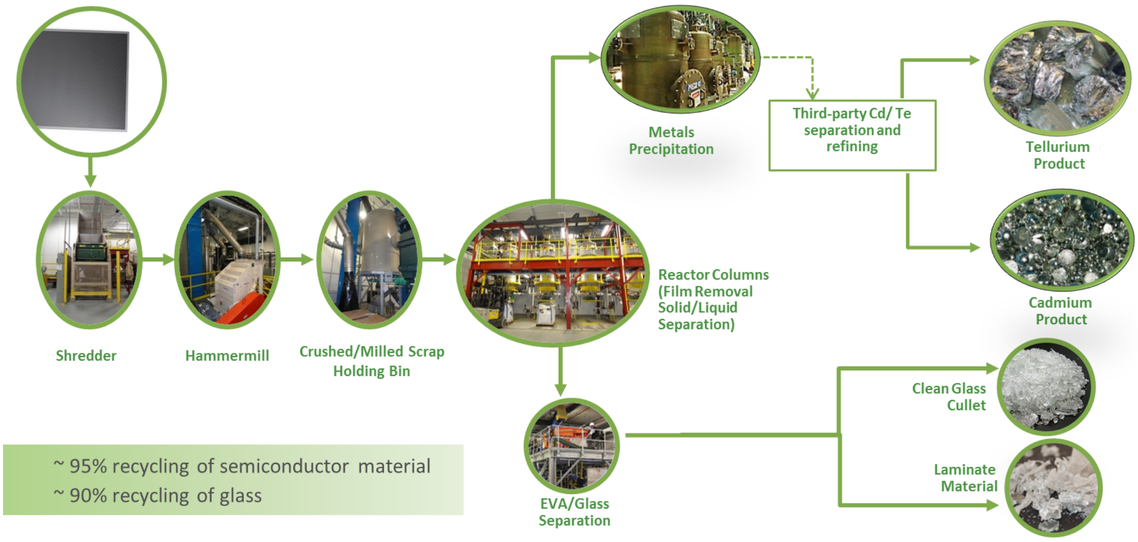


Figure 4 First Solar's module recycling technology version 2

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

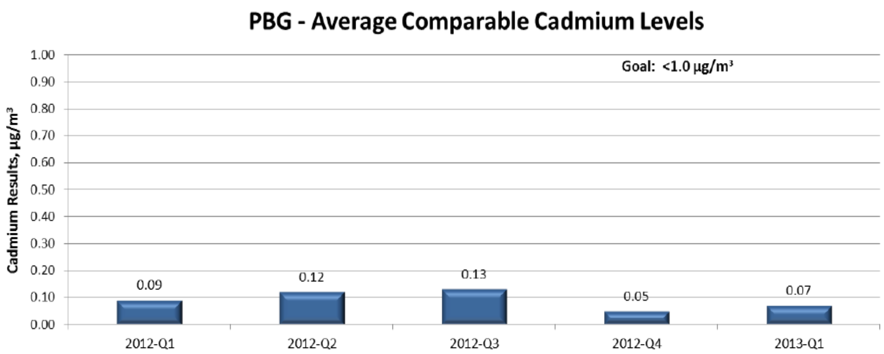
To prevent any EHS risks, First Solar has implemented continuous and effective control of the Cd indoor air concentrations, air emission levels and wastes concentrations. This control is also included during all maintenance operations.

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.



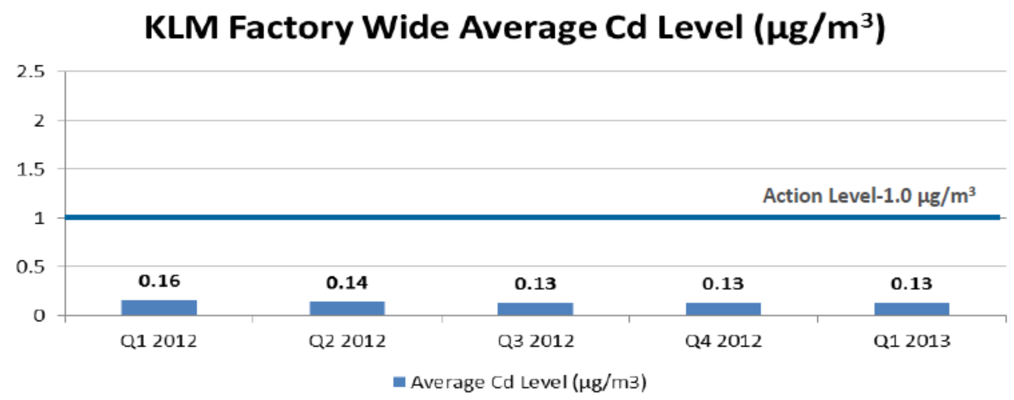


Figure 5 Perrysburg (U.S.) and Kulim (Malaysia) factories average Cd level (μg/m^3)

The action level of 1 μg/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 μg/m^3 and 5 μg/m^3, respectively, while First Solar has established its own more severe OEL limits of 5 μg/m^3 and 2.5 μg/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.

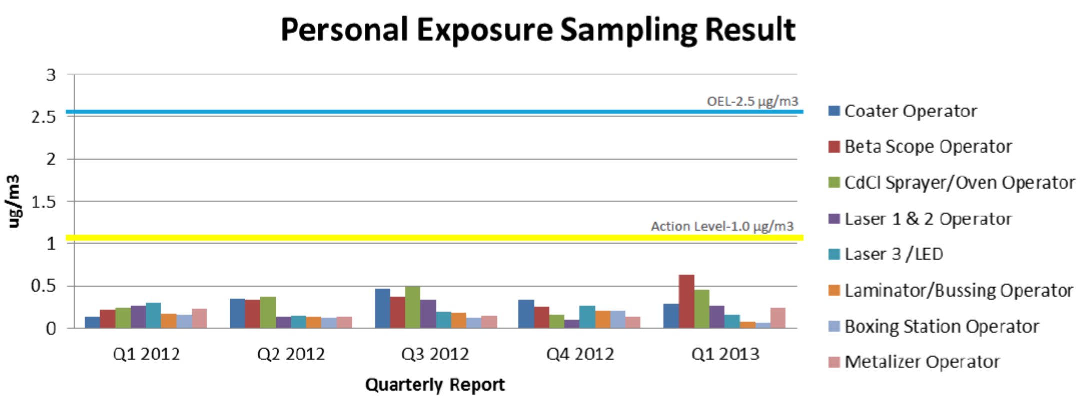


Figure 6 Personal exposure sampling (μg/m^3) by job function performed quarterly

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.

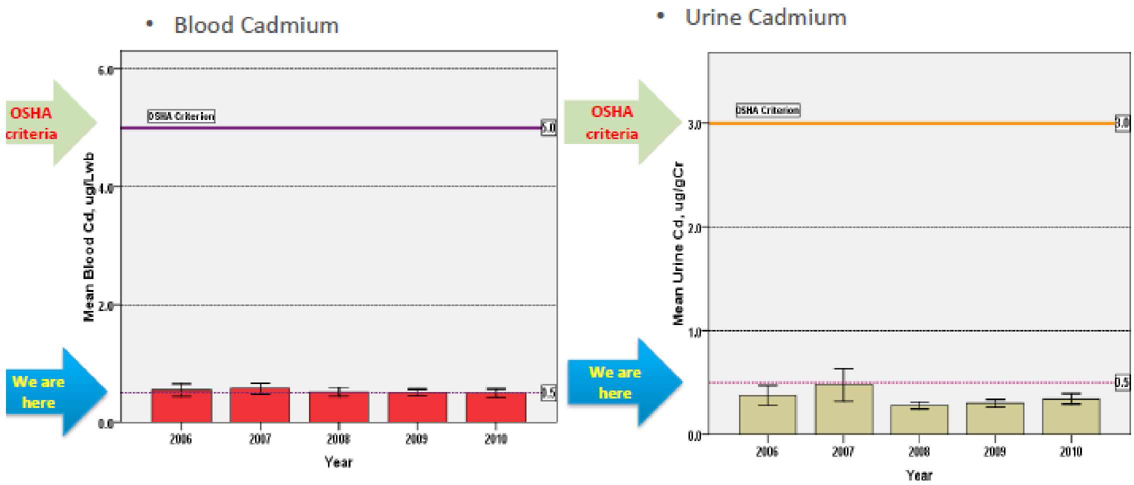


Figure 7 Perrysburg (U.S) factory mean Cd levels in blood and urine compared to OSHA biological limit

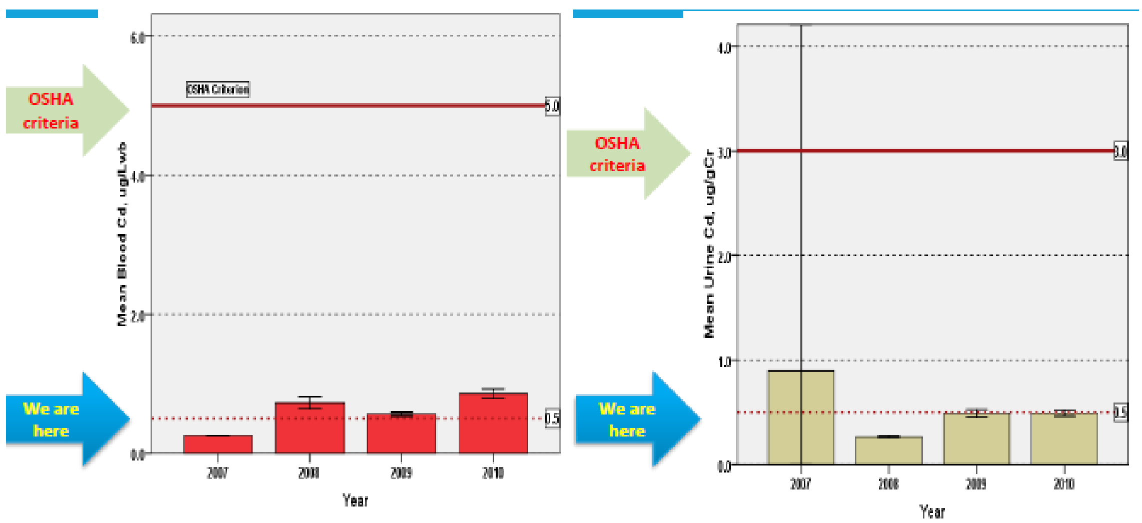


Figure 8 Kulim (Malaysia) factory mean Cd levels in blood and urine compared to OSHA biological limit

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 $5.34x10^{-9}$ 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.

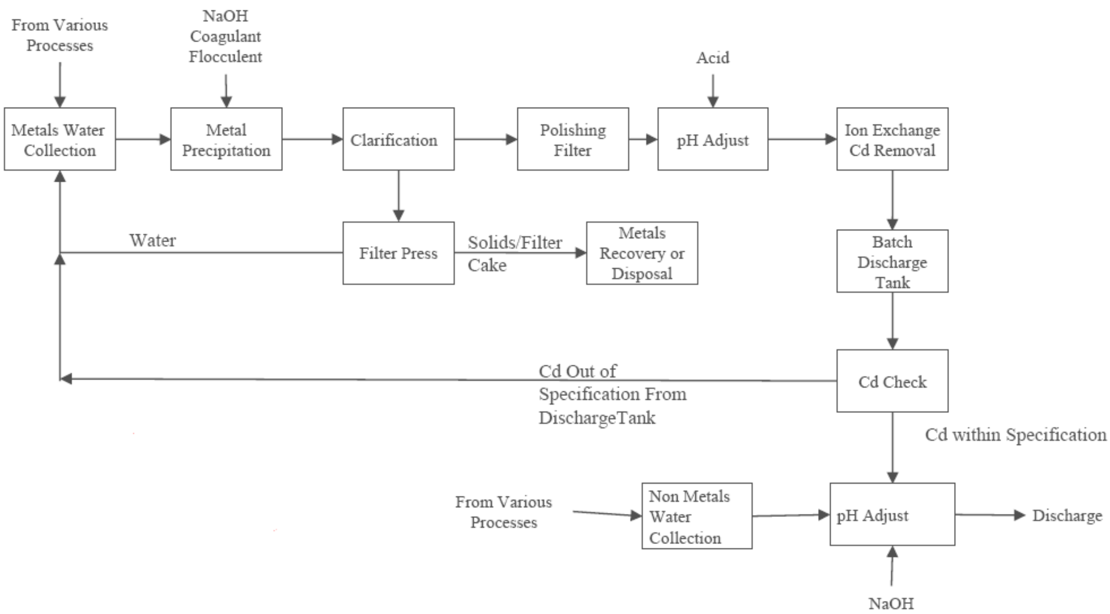


Figure 9 Wastewater treatment process flow diagram

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 $4.43x10^{-7}$ 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.

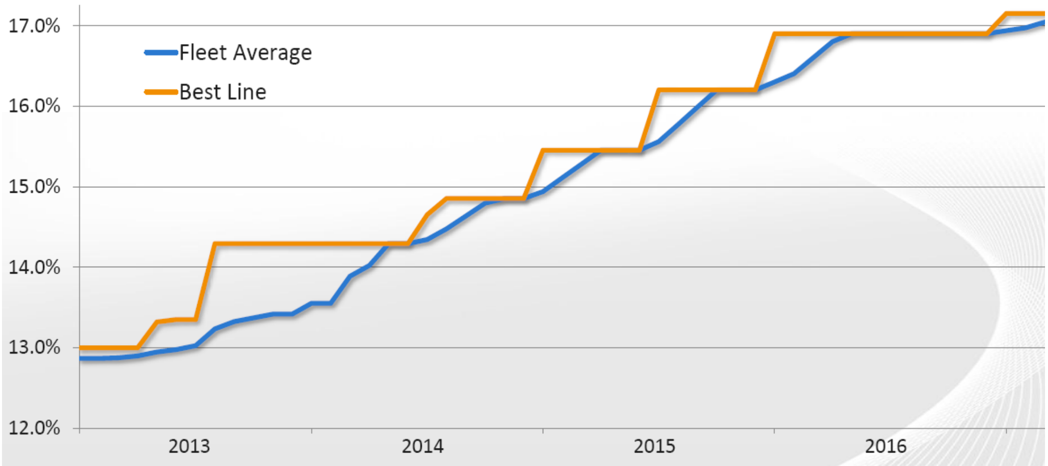


Figure 10 First Solar CdTe module efficiencies roadmap

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.

CENER

FCH FUNDACIÓN CHILE

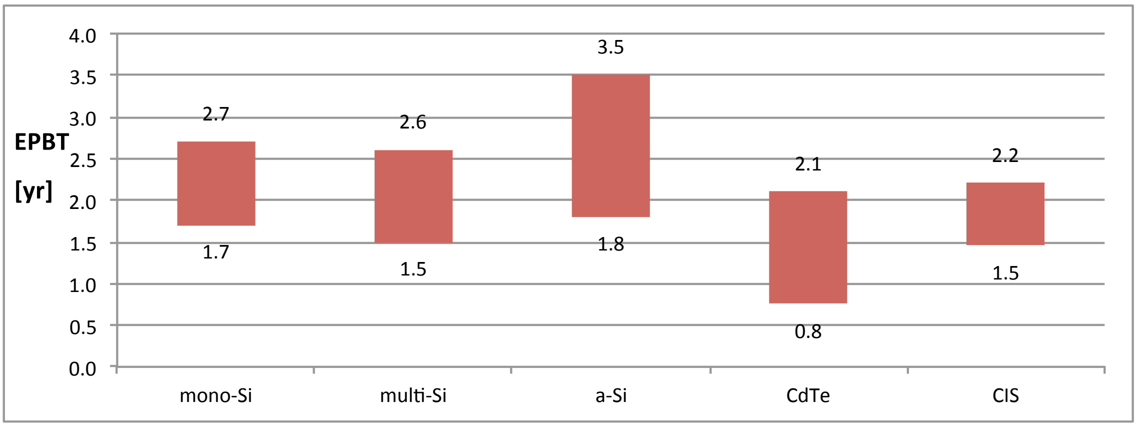


Figure 11 Energy Payback Time [yr] for different PV technologies. Irradiation standardized at 1700 kWh/m2/yr. Adapted from Peng et al., 2013

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.

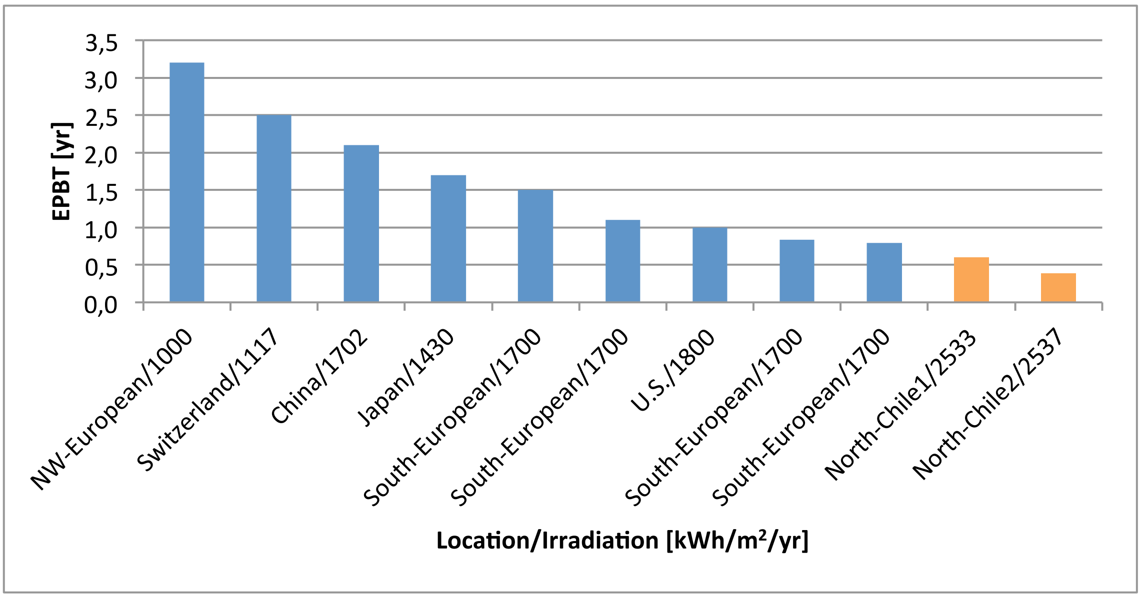


Figure 12 Energy Payback Time [yr] for CdTe PV at different locations and irradiations. Sources: Peng et al., 2013; this study.

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.

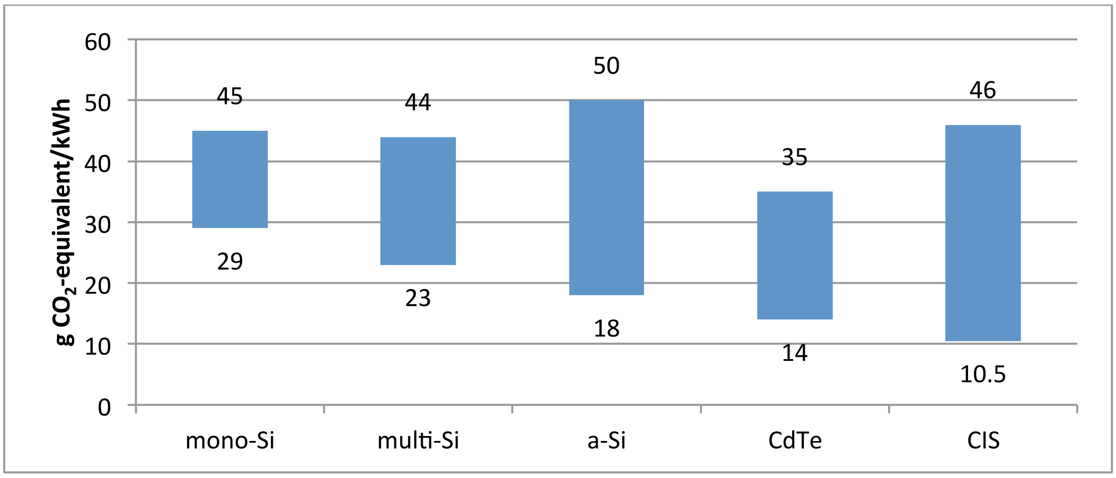


Figure 13 GHG emissions for different PV technologies. Irradiation standardized at 1700 [kWh/m2/yr]. Adapted from Peng et al., 2013.

[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/m²/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].

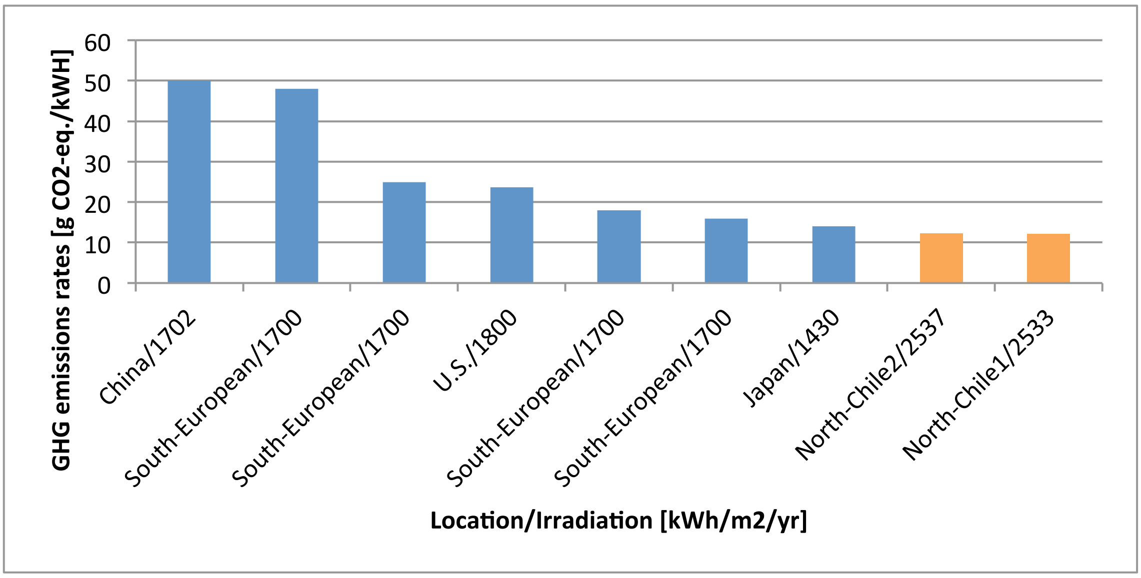


Figure 14 GHG emissions [g CO2-eq./kWh] for different PV technologies and irradiations[25].

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]

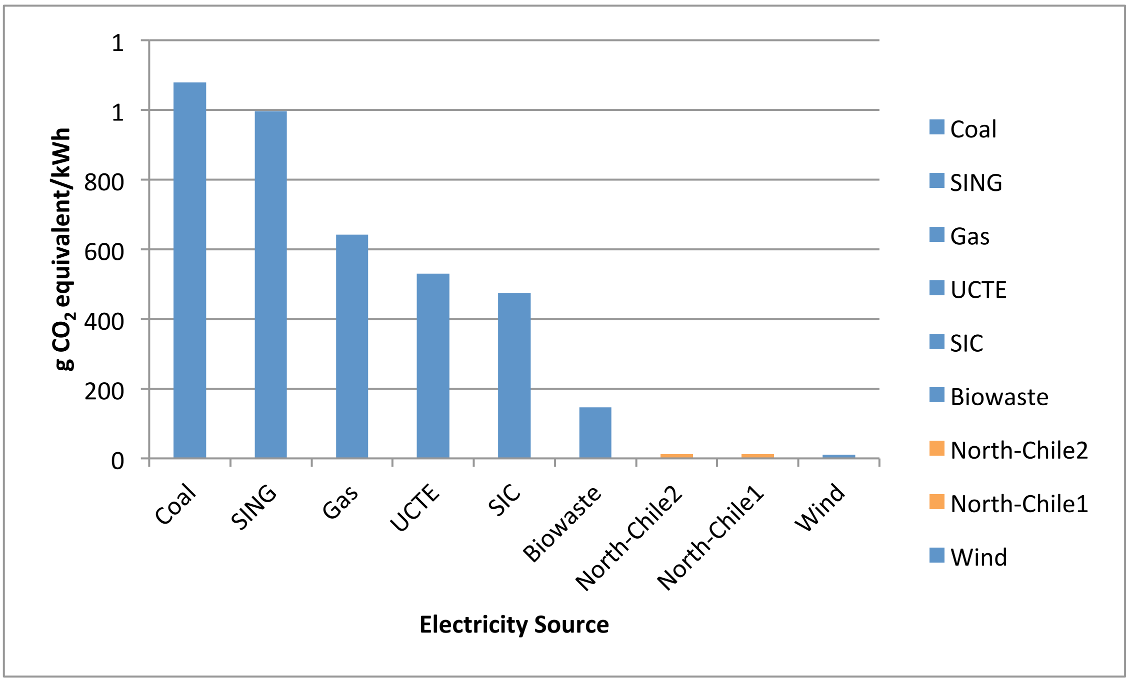


Figure 15 GHG emissions [g CO2-eq./kWh] for different electricity sources.

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.

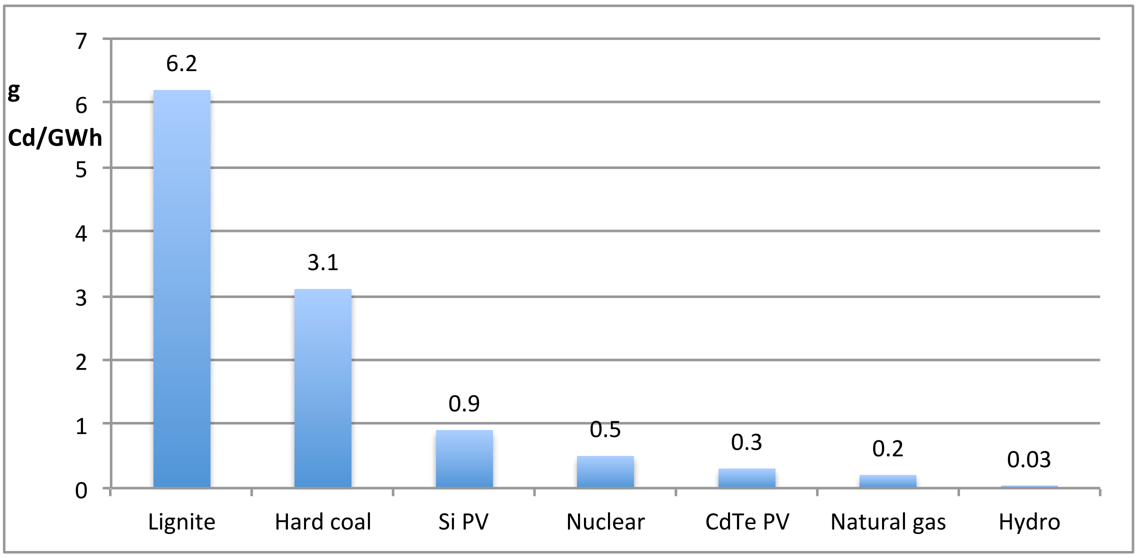


Figure 16 Life cycle atmospheric Cd emissions for different electricity generation options, Southern European conditions. Source: Fthenakis et al., 2008

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.

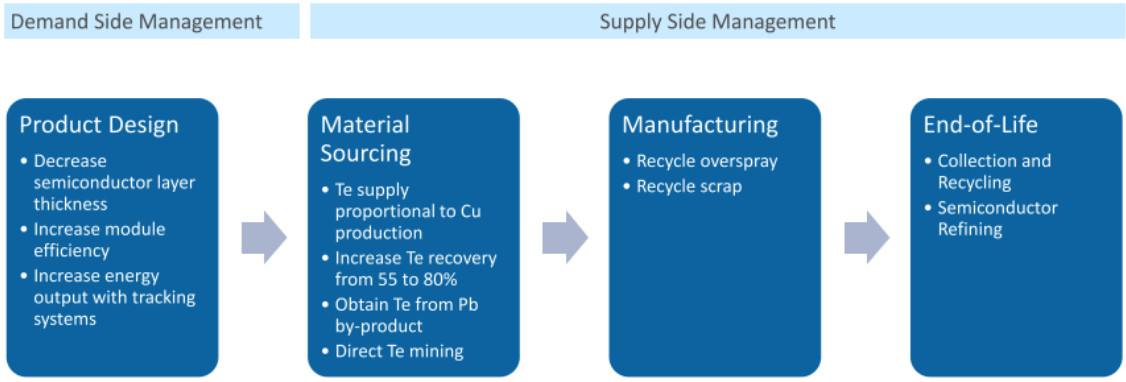


Figure 17 Life cycle management strategies for tellurium availability.[37]

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.

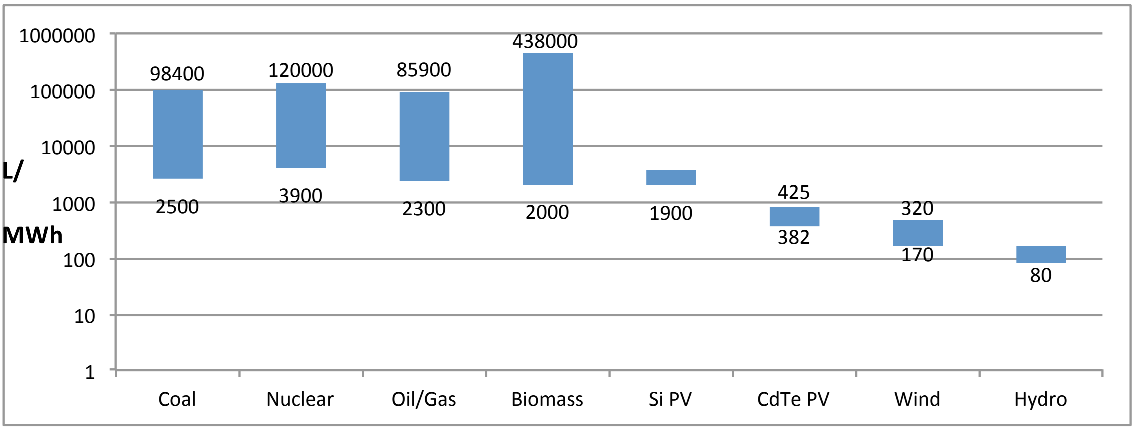


Figure 18 Life cycle water withdrawal for different energy generation options (Sources: Fthenakis and Kim, 2010; Sinha et al., 2013)

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.

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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

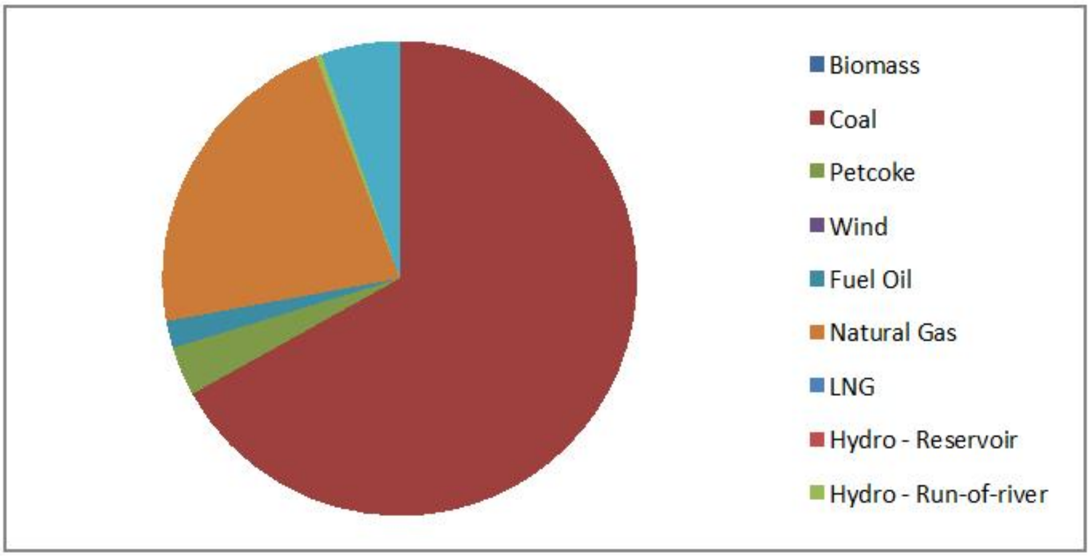
3.- APPENDICES

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

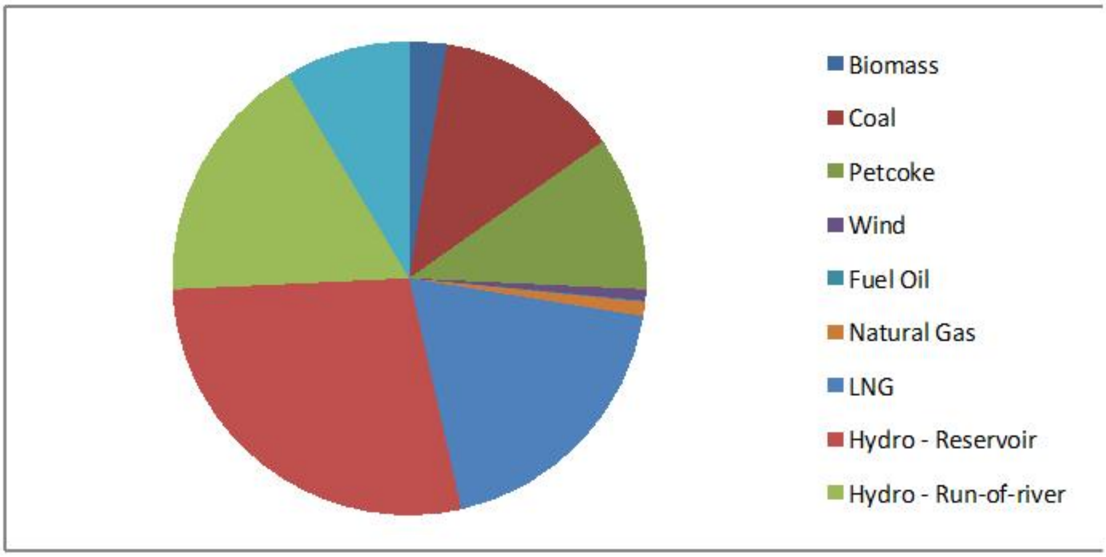
Primary Energy Source	2010	2011	2012	Average
Biomass	0,0%	0,0%	0,0%	0,00%
Coal	48,5%	69,6%	82,5%	66,87%
Petcoke	9,4%	0,2%	0,4%	3,35%
Wind	0,0%	0,0%	0,0%	0,00%
Fuel Oil	2,6%	1,8%	1,2%	1,86%
Natural Gas	26,8%	25,8%	13,6%	22,08%
LNG	0,0%	0,0%	0,0%	0,00%
Hydro – Reservoir	0,0%	0,0%	0,0%	0,00%
Hydro – Run-of-river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