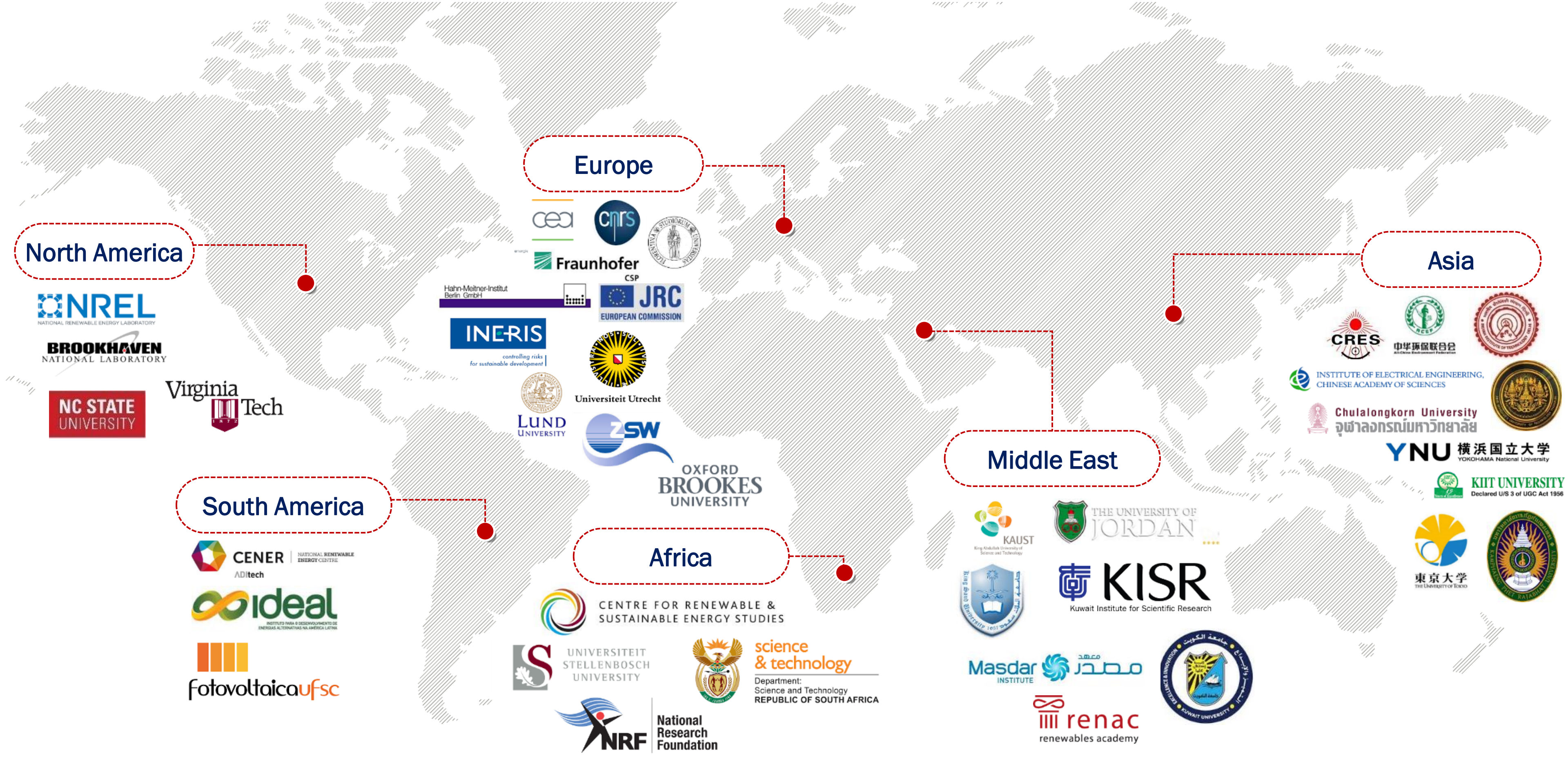
# 50+ RESEARCHERS HAVE CONFIRMED THE SAFETY AND BENEFITS OF CdTe PV



# LIST OF RESEARCHERS FROM U.S. AND INTERNATIONAL INSTITUTIONS

| | |
|---|---|
| Ken Zweibel | National Renewable Energy Laboratory (NREL) |
| Prof. Vasilis Fthenakis | Brookhaven National Laboratory (BNL) |
| Tommy Cleveland | North Carolina Clean Energy Technology Center (North Carolina State University) |
| Prof. William Reynolds, Jr.<br>Prof. Michael Karmis | Virginia Center for Coal and Energy Studies at Virginia Tech University |
| Arnulf Jäger-Waldau | European Commission’s Joint Research Center |
| Michael Held | Fraunhofer Institute for Building Physics |
| Dr. Christian Hagendorf<br>Dr. Matthias Ebert | Fraunhofer Center for Silicon Photovoltaics |
| Prof. Dr. Ralf B. Wehrspohn | Fraunhofer Institute for Mechanics of Materials |
| Dr. Marco Raugei | Oxford Brookes University |
| Dr. Daniel Lincot | French National Centre for Scientific Research (CNRS) |
| Dr. Ana Rosa Lagunas<br>Dr. Jaione Bengoechea<br>Dr. María Jesús Rodriguez | National Renewable Energy Centre of Spain (CENER) |
| Dr. Paola Finetti<br>Dr. Ugo Bardi | University of Florence |
| Prof. Martha Ch. Lux-Steiner | Hahn-Meitner Institut Berlin |

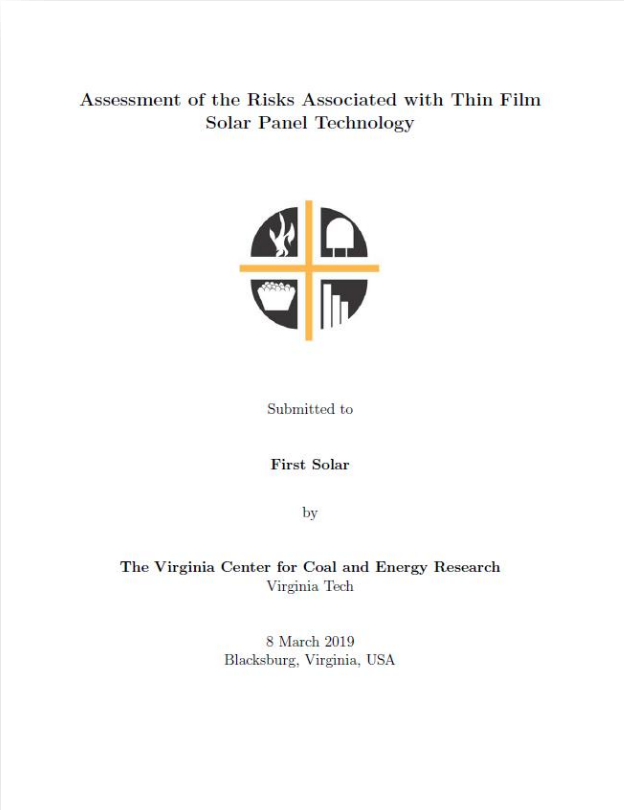
# LIST OF RESEARCHERS FROM U.S. AND INTERNATIONAL INSTITUTIONS (CONT.)

| | |
|---|---|
| Prof. Ricardo Ruther | Fotovoltaica/UFSC Solar Energy Research Laboratory at the Federal University of Santa Catarina (UFSC) |
| | Institute for the Development of Renewable Energies in Latin America (IDEAL) |
| Marco Lofat<br>Alejandro Florenzano | Fundación Chile |
| Dr. AJ Rix<br>Dr. JDT Steyl<br>Me. J. Rudman<br>U. Terblanche<br>Prof. JL van Niekerk | Centre for Renewable and Sustainable Energy Studies at Stellenbosch University |
| Prof. Viresh Dutta<br>Dr. K.Vamsi Krishna<br>Prof. T.R. Sreekrishnan | Indian Institute of Technology Delhi |
| Prof. Udai P. Singh | Kalinga Institute of Industrial Technology (KIIT) |
| Dr. A.R.M. Alamoud | King Saud University (KSU) |
| Dr. –Ing. Hasan Albusairi | Kuwait Institute for Scientific Research (KISR) |
| | Renewables Academy AG (RENAC) |
| Prof. Mohammed Al-Sarawi | Kuwait University |
| Prof. Ahmed Al-Salaymeh<br>Prof. Mohammad Hamdan<br>Dr. Ibrahim Odeh | University of Jordan |
| Dr. Raed Bkayrat | King Abdullah University of Science and Technology (KAUST) |

# LIST OF RESEARCHERS FROM U.S. AND INTERNATIONAL INSTITUTIONS (CONT.)

| | |
|---|---|
| Prof. Simo O. Pehkonen<br>Dr. Sgouris Sgouridis | Masdar Institute of Science and Technology |
| Dr. Xiangxin Liu | The Institute of Electrical Engineering (IEE) of Chinese Academy of Sciences (CAS) |
| Dr. Jianping Wang | All China Environment Federation |
| Dr. Yasunari Matsuno | The University of Tokyo |
| Dr. Hiroki Hondo | Yokohama National University |
| Dr. Surawut Chuangchote<br>Dr. Prapat Pongkiatkul | King Mongkut University of Technology |
| Dr. Manaskorn Rachakornkij<br>Dr. Chanathip Pharino<br>Dr. Thantip Punmatharith | Chulalongkorn University |
| Dr. Chulalak Changul | Phranakorn Rajabhat University |
| Alain Million | French Alternative Energies and Atomic Energy Commission (CEA) |
| Erik Alsema | Utrecht University |
| Rodolphe Gaucher | French National Institute for Industrial Environment and Risks (INERIS) |
| Prof. Hansjörg Gabler | Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) |
| Prof. Thomas B. Johansson | Internation Institute for Industrial Environmental Economics at Lund University |

# VIRGINIA TECH PEER REVIEW (2019): EXECUTIVE SUMMARY



Assessment of the Risks Associated with Thin Film Solar Panel Technology

Submitted to

**First Solar**

by

**The Virginia Center for Coal and Energy Research**
Virginia Tech

8 March 2019
Blacksburg, Virginia, USA

"Based upon the **potential environmental health and safety impacts of CdTe photovoltaic installations** across their life cycle, it is concluded they **pose little to no risk under normal operating conditions** and **foreseeable accidents** such as fire, breakage, **and extreme weather events** like tornadoes and hurricanes." Specifically, it was found that:

- The CdTe compound is less leachable and less toxic than elemental Cd.
- The encapsulation bond strength is on the order of ~50 kg/$cm^2$ making it very difficult to separate the front and back of the module.
- A battery of electrical, static and dynamic loading, hail impact, thermal and humidity cycling, and light response tests are typically used to assess the reliability of manufactured panels.
- Risks to the environment arising from broken solar panels during adverse events are considered by reviewing experimental results, theoretical worst-case modeling, and observational data from historical events. In each case, the potential negative health and safety impacts of utility-scale photovoltaic installations are low.
- The fate of CdTe in PV modules in simulated fires and the predicted dispersal of CdTe by analytical models suggest CdTe cleanup following a fire should be straightforward with standard methods.
- Experience with severe storms suggest solar facilities are relatively resilient against high winds and flooding…but even with the larger number of broken panels, environmental tests demonstrated CdTe was not released into the environment.
- Real-time monitoring helps ensure panels that become damaged by adverse events like storms are located immediately and quickly repaired or taken out of service.
- Because of the small quantity and low solubility of semiconductor material and the module encapsulation, the modules are characterized as federal non-hazardous waste at end-of-life using the Toxicity Characteristic Leaching Procedure.
- Weather also plays an important role in the economy of photovoltaic technologies. Given [Virginia's temperature and humidity], the leading utility-scale PV technology is arguably thin film CdTe PV.

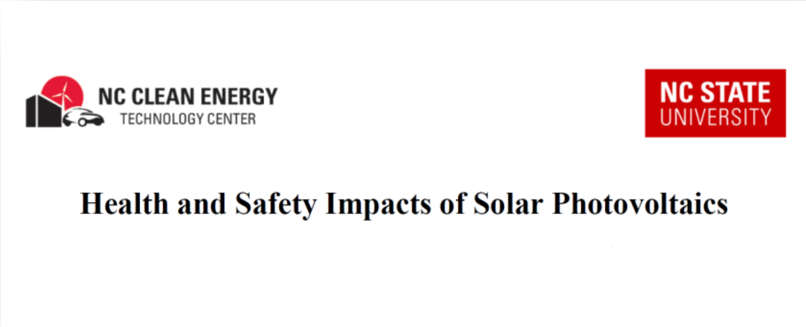
# EU PEER REVIEW (2017): EXECUTIVE SUMMARY

| | |
|---|---|
| Project title | Assessment of performance, environmental, health, and safety aspects of First Solar's CdTe PV technology |
| Client | First Solar Inc. |
| Report number | 30.2945.0-01 |
| Project authors | Dr. Christian Hagendorf<br>Group Manager Diagnostics of Solar Cells<br>Dr. Matthias Ebert<br>Manager Reliability of Solar Modules and Systems<br>*Responsible for Quality management and field performance section*<br>Fraunhofer CSP |
| | Dr. Marco Raugei<br>Senior Research Fellow<br>*Responsible for Life cycle impacts of the large-scale deployment of the CdTe technology and comparison with other technologies section*<br>OXFORD BROOKES UNIVERSITY |
| | Dr. Daniel Lincot<br>Senior Researcher<br>*Responsible for First Solar's CdTe technology and cost roadmaps and hot and humid and Performance under specific conditions sections*<br>cnrs |
| | Dr. Jaione Bengoechea<br>Senior Researcher<br>Dr. María Jesús Rodríguez<br>Head of Solar Cells Laboratory<br>*Responsible for Environmental, health, and safety aspects of First Solar's CdTe technology section*<br>CENER ADItech |
| Project coordinated and approved by | Dr. Ana Rosa Lagunas<br>Photovoltaic Department Director<br>CENER ADItech<br>*Responsible for project coordination and approval* |
| Project dates | Start date: April 2016 End date: January 2017 |

"From most points of view, a **large-scale deployment of CdTe PV** technology would have **positive long-term effects on the environment**, and **would not represent a health risk** for the public **during operation and foreseeable accidents.**" Specifically it was found that:

- If CdTe PV technology was deployed to displace conventional fossil fuel-based electricity generation, the benefits in terms of reduced greenhouse gas emissions would be between one and two orders of magnitude.
- From the points of view of energy demand and carbon emissions, current CdTe PV is in a leading position amongst the range of commercial PV technologies.
- At the module level, CdTe technology is the fastest growing technology in efficiency, which compares now to Si average high volume production efficiencies at about 16%…The time between R&D and module production of 2 to 5 years represents a clear strength of First Solar's technology.
- In typical module operating field temperatures, the loss of power rating of the modules due to temperature increase is lower in CdTe modules as compared to c-Silicon modules.
- On a given cumulative production, the price of CdTe modules is lower by a factor of 4 to 5 compared to silicon wafer based technology…with the reason being the simpler production process of thin film technologies.
- Deploying CdTe PV in Europe would actually decrease the overall Cd emissions per unit of generated electricity, while providing a safe and almost fully recyclable temporary sequestration route for the oversupply of raw Cd that is expected in the future, due to the increasing demand for Zn (of which Cd is an unavoidable by-product)
- Less than 10% of the cumulative life-cycle Cd emissions were found to be related to the Cd actually contained in the PV modules, while the rest was due to the indirect Cd emissions caused by the fossil fuel electricity used in the PV manufacturing processes… virtually no Cd emissions were found to occur in the use phase, even in the case of accidental fires, since the Cd is only present as chemically stable compounds (i.e. CdTe and CdS or CdSe) that are enclosed and sealed within glass panes.
- CdTe differs from elemental Cd in that it is a strongly bonded compound with an extremely high chemical and thermal stability, which limits its bioavailability and its potential for exposure to humans and the environment.

# U.S. NORTH CAROLINA STATE UNIVERSITY (2017): EXECUTIVE SUMMARY


NC CLEAN ENERGY TECHNOLOGY CENTER

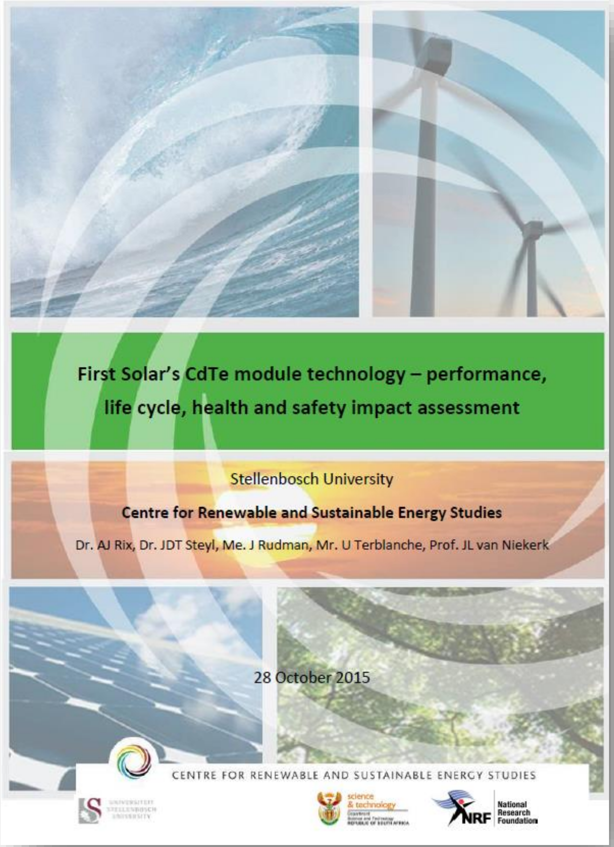
NC STATE UNIVERSITY

Health and Safety Impacts of Solar Photovoltaics

"Research demonstrates that [CdTe PV modules] pose **negligible toxicity risk** to public health and safety while **significantly reducing the public's exposure to cadmium** by reducing coal emissions." Specifically it was found that:

- All the approximately 7 grams of cadmium in one CdTe panel is in the form of a chemical compound cadmium telluride, which has 1/100th the toxicity of free cadmium.
- [CdTe] is a very stable compound that is non-volatile and non-soluble in water.
- Research has shown that the tiny amount of cadmium in these panels does not pose a health or safety risk.
- Even in the case of a fire, research shows that less than 0.1% of the cadmium is released when a CdTe panel is exposed to fire. The fire melts the glass and encapsulates over 99.9% of the cadmium in the molten glass.
- In a worst-case scenario of damaged panels abandoned on the ground, insignificant amounts of cadmium will leach from the panels.
- Testing shows that silicon and CdTe panels are both safe to dispose of in landfills, and are also safe in worst case conditions of abandonment or damage in a disaster.
- Analysis by local engineers has found that the current salvage value of the equipment in a utility scale PV facility generally exceeds general contractor estimates for the cost to remove the entire PV system.

# SOUTH AFRICA PEER REVIEW (2015): EXECUTIVE SUMMARY




"First Solar's CdTe thin film technology modules are a **technically feasible**, **environmentally friendly** and **safe option to producing electricity** in South Africa."

Specifically, it was found that:

1. First Solar thin film CdTe technology is suited for South Africa, with warmer climate areas **generating a higher yield** with the CdTe modules than for single or multi-crystalline silicon PV modules

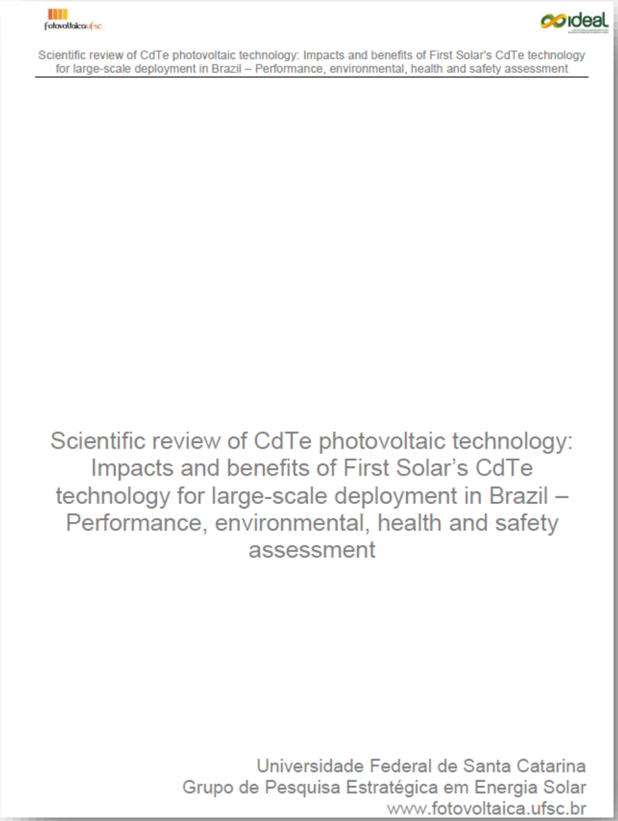
2. CdTe is **at least 8.9 times safer than Cd** with respect to acute exposure via inhalation or ingestion

3. The solid semiconductor compound CdTe is a crystalline, non-flammable powder, practically insoluble in water and with a **melting point above the typical temperature reached in veld fires**

4. Silicon-based PV has a higher life cycle water consumption level than CdTe due to the water needed for high-purity silicon production

5. CdTe PV modules also have **shorter energy payback times and lower life cycle $CO_2$ emissions** than any other PV modules and have comparable or less $CO_2$ emissions than nuclear and wind technologies

# BRAZIL PEER REVIEW (2014): EXECUTIVE SUMMARY


fotovoltaica ufsc

ideal

Scientific review of CdTe photovoltaic technology: Impacts and benefits of First Solar's CdTe technology for large-scale deployment in Brazil – Performance, environmental, health and safety assessment

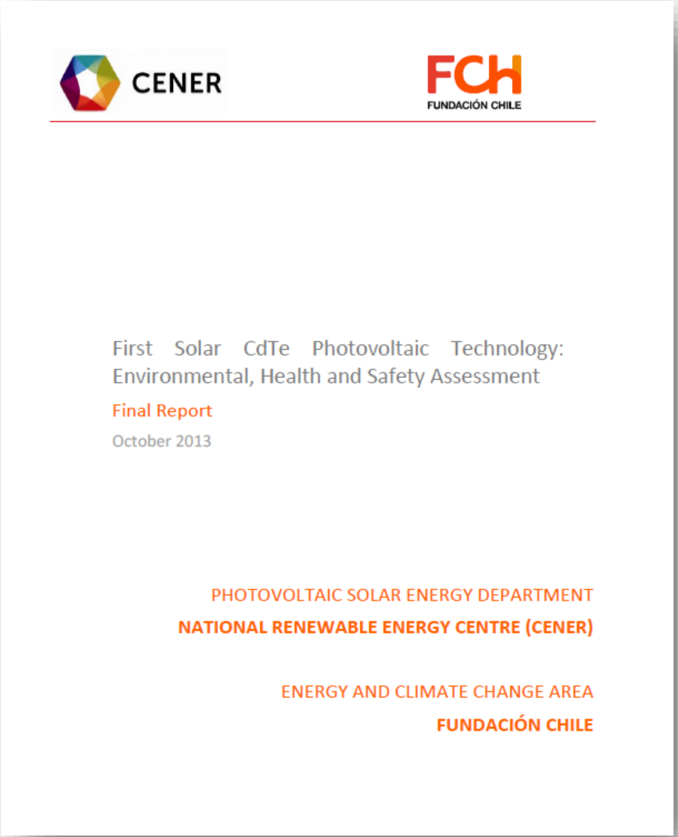
Scientific review of CdTe photovoltaic technology: Impacts and benefits of First Solar's CdTe technology for large-scale deployment in Brazil – Performance, environmental, health and safety assessment

Universidade Federal de Santa Catarina
Grupo de Pesquisa Estratégica em Energia Solar
www.fotovoltaica.ufsc.br

"CdTe PV is one of the **most adequate solar energy generation technologies for the Brazilian climatic conditions** and that CdTe PV systems **do not represent an environmental, health, or safety risk** under normal operating conditions and foreseeable accidents." Specifically, it was found that:

1. Compared with other PV technologies…the lower temperature coefficient of power of CdTe PV renders it a **better performer under the high operating temperatures** prevailing in the field, especially in warm and sunny countries like Brazil
2. Toxicity studies show that **CdTe is less toxic than elemental Cd**
3. In case of PV module breakage, **chemical degradation is unlikely** due to the low vapor pressure and low solubility of this compound and due to product design
4. The amount of energy that a CdTe PV module or power plant will be **able to generate** in Brazil over its +25 years lifetime is **up to 30 times larger than the energy required to produce** that same PV module or solar power plant
5. PV power plants can **generate more electricity per occupied area** than large hydropower plants operating in Brazil
6. CdTe PV provides a **good combination of large-scale industrial processing and field performance**, making it a **cost-effective technology for utility-scale PV plants** in Brazil

# CHILE PEER REVIEW (2013): EXECUTIVE SUMMARY



CENER

FCH
FUNDACIÓN CHILE

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

Final Report

October 2013

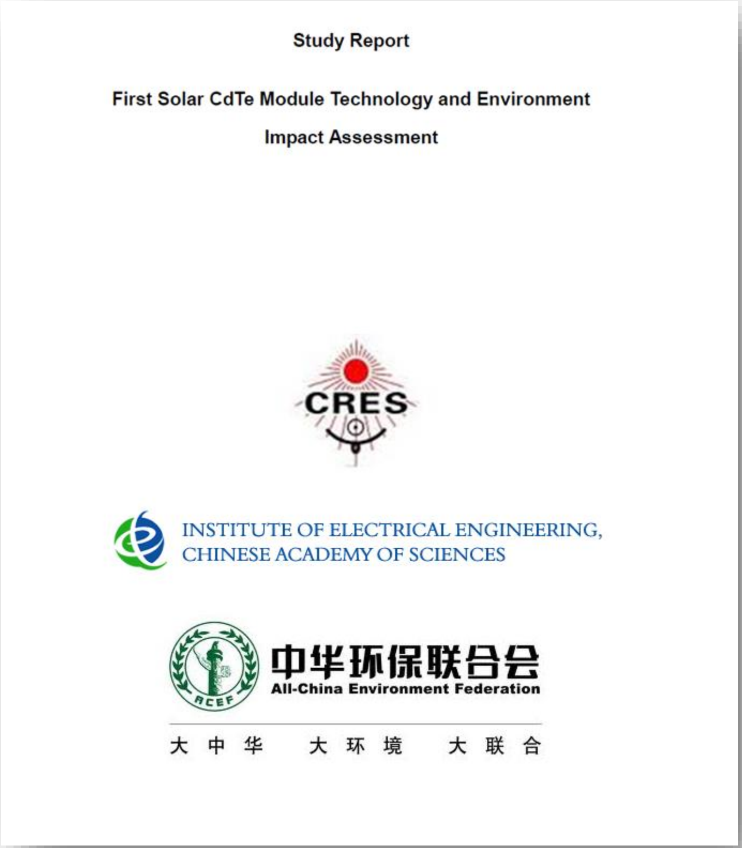
PHOTOVOLTAIC SOLAR ENERGY DEPARTMENT
NATIONAL RENEWABLE ENERGY CENTRE (CENER)

ENERGY AND CLIMATE CHANGE AREA
FUNDACIÓN CHILE

"From a life cycle perspective, CdTe PV technology is a **preferable option in environmental terms** when compared to fossil fuels as well as to… other PV technologies, considering **greenhouse gas emissions**, **energy payback time**, **water use**, **cadmium emissions** and impacts on **biodiversity**." Specifically, it was found that:

1. During normal operating conditions, First Solar's CdTe PV modules **emit zero pollutants** to the air, water and soil
2. 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
3. If an **earthquake** were to happen… we maintain the conclusion that a **broken module** from First Solar CdTe technology can be classified as **zero risk**
4. 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**
5. **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
6. 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
7. Concerning manufacturing operations, First Solar has continuously implemented **outstanding policies, practice, procedures and management system** in order to protect **workers' health and safety**

# CHINA PEER REVIEW (2013): EXECUTIVE SUMMARY



Study Report

First Solar CdTe Module Technology and Environment

Impact Assessment

CRES

INSTITUTE OF ELECTRICAL ENGINEERING,
CHINESE ACADEMY OF SCIENCES

中华环保联合会
All-China Environment Federation

ACEF

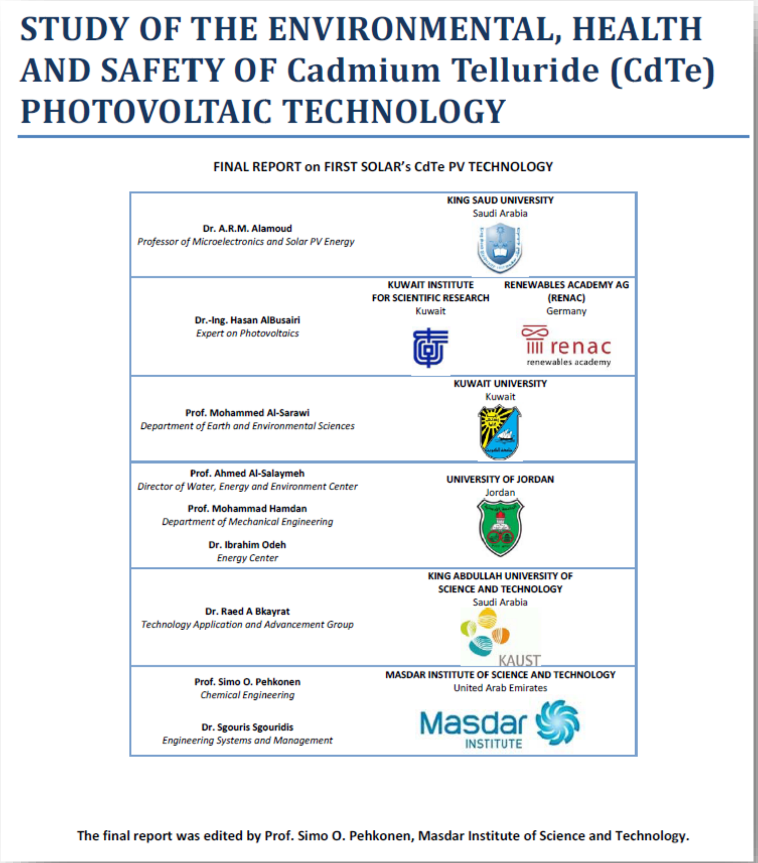
大 中 华 大 环 境 大 联 合

"Given the **low lifecycle $CO_2$ emissions** and **short energy payback time** of CdTe PV, wide application may **effectively help** us realize the goal of **energy conservation and emission reduction**."

Specifically, it was found that:

1. CdTe modules presents the **best environmental performance** in terms of energy payback time and carbon emission rate due to its low life-cycle energy requirement and relatively high conversion efficiency
2. CdTe is a **very stable compound**, less toxic than elemental Cd
3. CdTe modules **will not emit any Cd compounds** under normal operation
4. Under average module breakage rate (0.04%/year), since **CdTe is thin** and in small quantity, **even release of all Cd** in modules **is highly unlikely to pose a potential health risk** to on-site workers or off-site residents
5. Generating power with CdTe PV modules is an **effective way to control Cd** pollution
6. First Solar has been adopting **excellent management system processes and policies** during module production and recycling to **protect the environment and workers' health** and safety
7. It is **advisable that China includes CdTe**, a competitive PV generation technology, into its 13th Five-year Plan **as a commercial-scale PV technology**, and improve its CdTe research and production technology level

# MIDDLE-EAST PEER REVIEW (2012): EXECUTIVE SUMMARY



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

FINAL REPORT on FIRST SOLAR's CdTe PV TECHNOLOGY

| | |
|---|---|
| **Dr. A.R.M. Alamoud**<br>*Professor of Microelectronics and Solar PV Energy* | KING SAUD UNIVERSITY<br>Saudi Arabia |
| **Dr.-Ing. Hasan AlBusairi**<br>*Expert on Photovoltaics* | KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH<br>Kuwait<br>RENEWABLES ACADEMY AG (RENAC)<br>Germany<br>renac renewables academy |
| **Prof. Mohammed Al-Sarawi**<br>*Department of Earth and Environmental Sciences* | KUWAIT UNIVERSITY<br>Kuwait |
| **Prof. Ahmed Al-Salaymeh**<br>*Director of Water, Energy and Environment Center*<br>**Prof. Mohammad Hamdan**<br>*Department of Mechanical Engineering*<br>**Dr. Ibrahim Odeh**<br>*Energy Center* | UNIVERSITY OF JORDAN<br>Jordan |
| **Dr. Raed A Bkayrat**<br>*Technology Application and Advancement Group* | KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY<br>Saudi Arabia<br>KAUST |
| **Prof. Simo O. Pehkonen**<br>*Chemical Engineering*<br>**Dr. Sgouris Sgouridis**<br>*Engineering Systems and Management* | MASDAR INSTITUTE OF SCIENCE AND TECHNOLOGY<br>United Arab Emirates<br>Masdar INSTITUTE |

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

"The key findings of the peer review support the notion that **CdTe PV technology can contribute to large-scale deployment of renewable energy** solutions in an **environmentally sustainable way** addressing the increasing global demand for low-carbon energy." Specifically, it was found that:

1. The use of CdTe PV can **contribute to the mitigation of greenhouse gas emissions**
2. CdTe PV has a **lower carbon footprint** than crystalline silicon- based solar technologies considering the entire life cycle and a relatively **short energy-payback time** compared to other competing technologies
3. The usage of CdTe in PV applications may be regarded as **beneficial to the environment by sequestering a considerable amount of cadmium**, which is a waste product of Zinc production
4. **Emissions of Cadmium (Cd) compounds** into the ambient environment during the entire PV module lifecycle are **minimal**
5. **CdTe** has been shown to be **far less toxic than elemental Cd**
6. It is **possible to ensure worker and environmental safety** by implementing best practices for monitoring and management systems at CdTe manufacturing facilities
7. The potential for cradle-to-cradle of **CdTe solar module recycling** is significant (with more than 95% material recovery rates). This recycling potential, in addition to the untapped Tellurium recovery sources from copper production, indicates that **Te availability** is **not expected to pose a threat to large-scale deployment** of CdTe PV systems

# JAPANESE PEER REVIEW (2013): EXECUTIVE SUMMARY

December 1, 2013

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

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

1. The Goal and Scope

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

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

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

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


Fig. 1 Large fire caused by tsunami in Kesenuma City on March 11, 2011[4]

3. Hazard map data for earthquakes and tsunami

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

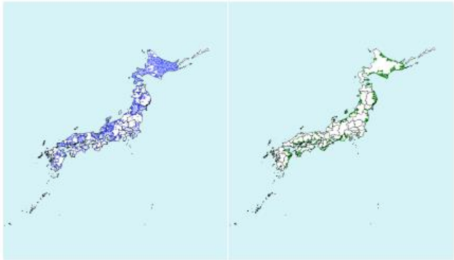


Fig. 2 Hazard map availability for earthquake (left) and Tsunami (right)

"The **environmental risks** of CdTe PV systems **under catastrophic events** can be **considered small.**" Specifically it was found that:

- Salt water leaching tests and tsunami modeling confirmed **Cd exposure would be minimal**
- CdTe is **insoluble in water** and **would not mobilize** into the environment
- Module **design encapsulates semiconductor**… preventing the exposure of CdTe to the environment under normal conditions, and greatly reducing potential exposure under broken-module conditions.
- Routine inspections and power monitoring result in **prompt removal** of broken modules
- Batch leaching tests were conducted [by the Central Research Institute of Electric Power Industry, Japan] with broken CdTe PV modules in the acid rain atmosphere (pH = 4.8, 40 centigrade) with continuous tumbling for 10 minutes to 72 hours… Cd concentrations were **below the minimum detectable quantity** in all leaching tests.
- Even in the worst case scenarios, it is **unlikely that the Cd concentrations** in air and sea water **will exceed the environmental regulation values**

# JAPANESE PEER REVIEW (2012): EXECUTIVE SUMMARY

**SCIENTIFIC REVIEW ON THE ENVIRONMENTAL AND HEALTH SAFETY (EHS) ASPECTS OF CADMIUM TELLURIDE (CDTE) PHOTOVOLTAIC (PV) SYSTEMS OVER THEIR ENTIRE LIFE CYCLE**

**FINAL REPORT on FIRST SOLAR's CdTe PV TECHNOLOGY**

| | |
|---|---|
| **Dr. Yasunari Matsuno,**<br>*Associate Professor* | 東京大学<br>THE UNIVERSITY OF TOKYO |
| **Dr. Hiroki Hondo**<br>*Professor* | Yokohama National University<br>横浜国立大学 |

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

Specifically, it was found that:

1. The **life cycle GHG emissions** and **energy payback time** of First Solar's CdTe PV technology are the **lowest among all current PV technologies**
2. CdTe PV technology has **lower cadmium emissions compared with coal and oil** fired power generation during its life cycle
3. **In the foreseeable accidents** (e.g. fire, breakage), the **emissions of Cd** or Cd compounds have been proven to be **negligibly small**
4. **CdTe is less toxic than Cd**
5. With the potential for a Cd oversupply problem in the near future, CdTe PV systems should be considered as **one of the solutions for a sustainable use of Cd**
6. Concerning manufacturing operations, **First Solar has continuously implemented outstanding policies, practices, procedures and management systems** in order **to protect worker's health and safety as well as the environment.** Actual air and water emissions of cadmium are well below the local regulatory limits in all factories

# INDIAN PEER REVIEW (2012): EXECUTIVE SUMMARY

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

**FINAL REPORT on FIRST SOLAR's CdTe PV TECHNOLOGY**


**Viresh Dutta (PI)**
*Professor at the Photovoltaic laboratory and Centre for Energy Studies*

**Dr. K.Vamsi Krishna (Co-PI)**
*Professor at the Centre for Energy Studies*

**T.R. Sreekrishnan (Co-PI)**
*Professor and Head of Department of Biochemical Engineering*

**Udai P. Singh (Co-PI)**
*Professor at the School of Electronics Engineering*


"There are **no direct adverse effects from the PV industry on environment and health**" and that "overall, **large-scale, ground-mounted solar PV power plants are largely beneficial** with regards to environmental indicators relative to traditional fossil-fuel based power generation." Specifically, it was found that:

1. PV systems, particularly using the CdTe have **significant potential to mitigate global warming**
2. CdTe PV has the **smallest carbon footprint** and **fastest energy payback** period among PV technologies
3. CdTe PV modules have about **half the GHG emissions of crystalline Si**
4. **Little or no possibility of cadmium (Cd) being released** from the modules deployed in the field
5. **A large growth in the CdTe PV sector** has the potential to **actually reduce**, rather than increase, overall **global Cd-related environmental pollution**
6. Whenever CdTe PV specifically replaces coal in power generation, it **lowers the associated Cd emissions to air by 100–360 times**
7. **CdTe differs from elemental Cd and other Cd compounds** due to strong bonding that leads to an extremely high chemical and thermal stability
8. CdTe based photovoltaics can act to **sequester Cd already being produced from Zinc and Copper mining** as a by-product
9. **High recycling recovery rates,** in addition to enhanced recovery during primary production, reduced thickness of semiconductor layers, increased efficiency and life expectancy of modules, **ease concerns of future raw material availability**

# THAI PEER REVIEW (2012) EXECUTIVE SUMMARY

**Review of Environmental, Health and Safety of CdTe Photovoltaic Installations throughout Their Life-Cycle**

FINAL REPORT on FIRST SOLAR'S CdTe PV TECHNOLOGY

**Dr. Surawut Chuangchote**
*The Joint Graduate School of Energy and Environment*

**Dr. Prapat Pongkiatkul**
*Department of Environmental Engineering*

**Dr. Manaskorn Rachakornkij**
*Center of Excellence on Hazardous Substance Management*
*Department of Environmental Engineering*

**Dr. Chanathip Pharino**
*Center of Excellence on Hazardous Substance Management*
*Department of Environmental Engineering*

จุฬาลงกรณ์มหาวิทยาลัย
Chulalongkorn University
Pillar of the Kingdom

**Dr. Thantip Punmatharith**
*Center of Excellence on Hazardous Substance Management*

**Dr. Chulalak Changul**
*Major of Building Technology Management*

"**CdTe PV systems are well suited for use in large-scale operations**," and "can **provide significant environmental benefits** for reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species."

Specifically it was found that:

1. In the overall lifecycle of CdTe PV, it is found to produce **minimal environmental emissions compared to other PV systems and energy generation** options
2. Under normal operation, CdTe PV modules **do not pose risk to human health or the environment**
3. **Installation workers do not have the possibility of exposure** to the semiconductor layer of the module **because it is encapsulated between two sheets of glass**
4. **In foreseeable accidents, emissions of Cd or Cd compounds have been proven to be negligibly small**, because the **Cd content would be encapsulated in the molten glass** matrix in case of fire, and because of the **low solubility of CdTe** in case of breakage
5. CdTe has **very low solubility** in water, and it can only be chemically etched by acids. A module would have to be **broken into small (mm-scale) pieces and agitated in acid** (similar to the recycling process) in order **to dissolve the semiconductor** materials
6. CdTe is **less toxic than elemental cadmium (Cd)**
7. CdTe PV systems that use Cd as a raw material should be considered as **one of the solutions for a sustainable use of Cd**
8. With an albedo value close to the values of grass, dry grass, and uncultivated fields, CdTe PV **does not cause the problem of high solar reflection** to the environment

# ITALIAN PEER REVIEW (2012): EXECUTIVE SUMMARY

**SUMMARY OF AN ENVIRONMENTAL, HEALTH AND SAFETY IMPACT EVALUATION OF CdTe PV INSTALLATIONS THROUGHOUT THEIR LIFE-CYCLE**


Dr. Paola Finetti

Dr. Ugo Bardi

*Department of Chemistry*


"With the **lowest energy payback time and carbon footprint** the **CdTe PV industry** can also **sustain faster growth rates** and still **retain a positive environmental impact profile."**

Specifically it was found that:

1. Replacing European or US grid electricity with CdTe PV power plants amounts to **89-98% reduction of greenhouse gas emission, pollutants and heavy metals including Cd**
2. For every GWh of electric energy produced, the life-cycle Cd release of CdTe PV is **over one hundred times smaller than Cd air emission from a fossil fuel power plant**
3. The **only measurable Cd emission that can be attributed to CdTe PV is due to the combustion of fossil fuels** used to generate the electricity required by manufacturing (and recycling) process
4. CdTe PV technology requires the smallest amount of energy for its manufacturing cycle, which means that CdTe PV is also the **weakest Cd emitter of all the PV technologies** available
5. PV power plants based on CdTe PV modules technology are **safe and compatible with agriculture.** Combining PV electricity production with agriculture can be very **beneficial for both activities**

# FRAUNHOFER INSTITUTE REVIEW (2012): EXECUTIVE SUMMARY

## Scientific Comment of Fraunhofer to Life Cycle Assessment of CdTe Photovoltaics


**Michael Held**
*Fraunhofer Institute for Building Physics*

**Dr. Christian Hagendorf**
*Fraunhofer Center for Silicon Photovoltaics*

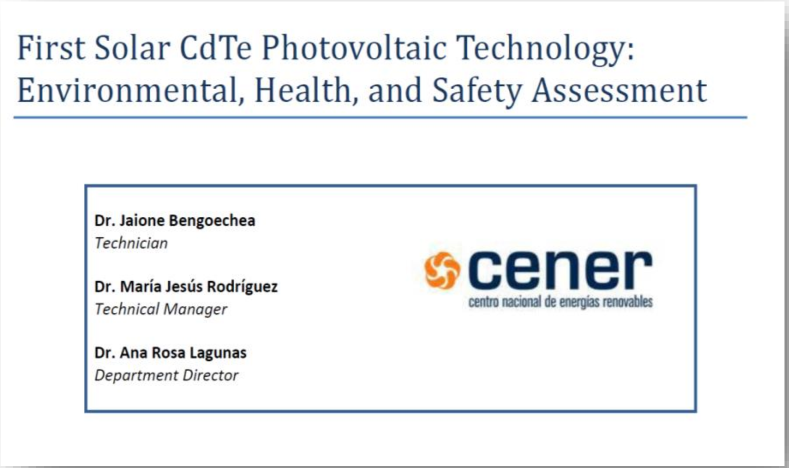
**Prof. Dr. Ralf B. Wehrspohn**
*Fraunhofer Institute for Mechanics of Materials*


Fraunhofer

"Concerning the risk and toxicity assessment of CdTe photovoltaic modules, the number of studies world wide indicate that **CdTe cannot be classified by Cd** in this particular application case and **regulation authorities have to define application specific regulation of CdTe.**"
Specifically it was found that:

- CdTe has **low acute inhalation, oral, and aquatic toxicity**, and is **negative in the Ames mutagenicity test**
- CdTe exhibits **aqueous solubility** and bioavailability properties that are **approximately two orders of magnitude lower than the 100% solubility and bioavailability of ionized cadmium chloride** ($CdCl_2$), which means that CdTe does not readily release the reactive ionic form of Cd ($Cd^{2+}$) upon contact with water or biological fluids
- EU mass concentration and standard leaching tests confirmed the European Waste classification of **CdTe PV modules** as **non-hazardous waste** and that they could be disposed of in ordinary landfills in accordance with European waste laws
- CdTe PV has been found to produce **environmental Cd emissions to air** that **are no higher than those from conventional silicon PV technologies** on a life cycle basis

# SPANISH PEER REVIEW (2010): EXECUTIVE SUMMARY



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

**Dr. Jaione Bengoechea**
*Technician*

**Dr. María Jesús Rodríguez**
*Technical Manager*

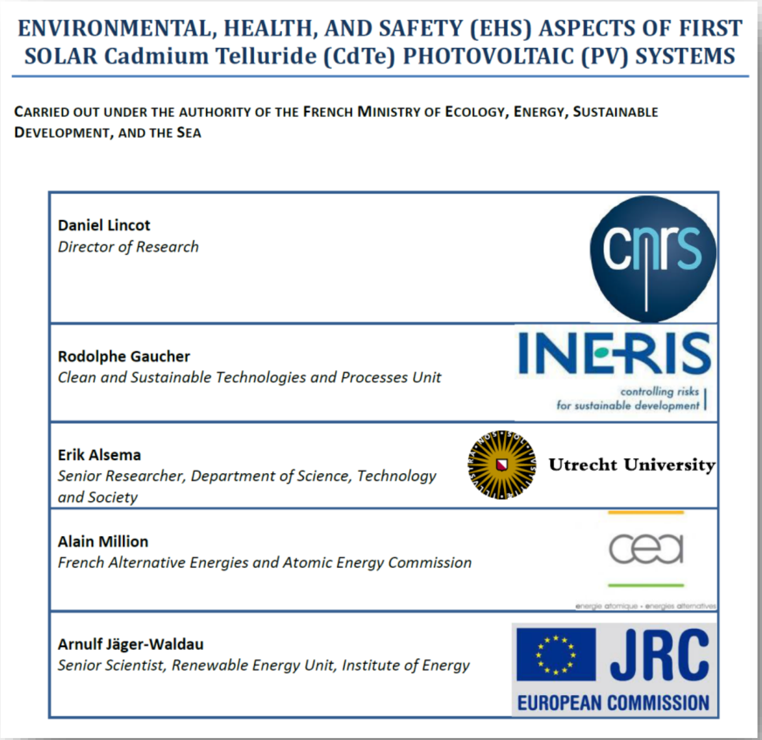
**Dr. Ana Rosa Lagunas**
*Department Director*

cener
centro nacional de energías renovables

“**First Solar’s CdTe PV technology presents a very positive environmental profile**,” and that “CdTe PV can **contribute to the mitigation of greenhouse gases emissions** to the atmosphere **with a negligible risk.**” Specifically it was found that:

1. First Solar’s CdTe PV technology has the **lowest carbon footprint, pollutant emissions (including Cd) and energy pay back time** among all current PV technologies, helping to **achieve rapid scalability and $CO_2$ reductions**
2. The generation of electricity by **PV produces no waste and uses little if any water**, in contrast to the combustion of fossil fuels, nuclear generation, and CSP solar technologies
3. During normal operating conditions, First Solar’s CdTe PV modules emit **zero pollutants to the air, water, and soil**
4. CdTe modules **do not represent any risk for human health nor for the environment**, during normal operating conditions and in the exceptional case of fire or breakage
5. On a lifecycle basis, First Solar’s CdTe PV technology has among the **lowest atmospheric cadmium (Cd) emissions of commonly used energy sources**
6. CdTe PV actually has **lower life cycle Cd emissions than the silicon wafer based PV technologies**, due primarily to the lower energy used for module production
7. First Solar’s CdTe PV modules provide a **beneficial and safe use for cadmium** that would otherwise be stored for future use or disposed of in landfills as hazardous waste

# FRENCH PEER REVIEW (2009): EXECUTIVE SUMMARY



**ENVIRONMENTAL, HEALTH, AND SAFETY (EHS) ASPECTS OF FIRST SOLAR Cadmium Telluride (CdTe) PHOTOVOLTAIC (PV) SYSTEMS**

CARRIED OUT UNDER THE AUTHORITY OF THE FRENCH MINISTRY OF ECOLOGY, ENERGY, SUSTAINABLE DEVELOPMENT, AND THE SEA


**Daniel Lincot**
*Director of Research*

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cnrs

INERIS
controlling risks
for sustainable development

Utrecht University

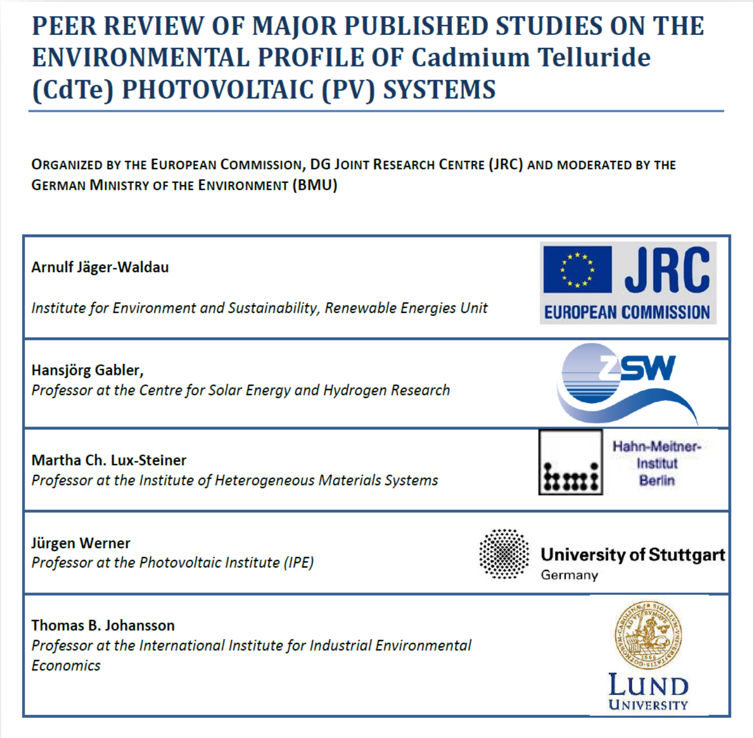
cea
energie atomique • energies alternatives

JRC
EUROPEAN COMMISSION

"**Large-scale deployment of CdTe PV can be considered safe to human health and the environment**," and that "**CdTe PV can contribute decisively** to the objective of a rapid reduction of $CO_2$ emissions in order **to combat climate change.**" Specifically it was found that:

1. First Solar's CdTe PV represents an important breakthrough in renewable energy technologies towards large-scale applications, **contributes decisively to the much-needed acceleration of PV deployment**, and has an **excellent environmental profile**
2. During standard operation of CdTe PV systems, there are **no cadmium emissions – to air, to water, or to soil**
3. **In the exceptional case of accidental fires or broken panels**, scientific studies show that **cd emissions remain negligible**
4. **Lowest carbon footprint among current PV technologies**, and **compares well with nuclear and wind** technologies
5. **Atmospheric life cycle emissions of cadmium** (Cd) from CdTe PV **are very low**; **liquid waste emissions are well below regulations** for wastewater effluents and progress continues to be made to reduce this level
6. **Policies, practices, and management systems** in place **protect the health and safety of its workers**
7. First Solar takes **a proactive risk assessment-based approach to EHS** issues and promotes continuous improvements to further reduce risks

# EUROPEAN UNION JRC PEER REVIEW (2005): EXECUTIVE SUMMARY



PEER REVIEW OF MAJOR PUBLISHED STUDIES ON THE ENVIRONMENTAL PROFILE OF Cadmium Telluride (CdTe) PHOTOVOLTAIC (PV) SYSTEMS

ORGANIZED BY THE EUROPEAN COMMISSION, DG JOINT RESEARCH CENTRE (JRC) AND MODERATED BY THE GERMAN MINISTRY OF THE ENVIRONMENT (BMU)

**Arnulf Jäger-Waldau**
*Institute for Environment and Sustainability, Renewable Energies Unit*

**Hansjörg Gabler,**
*Professor at the Centre for Solar Energy and Hydrogen Research*

**Martha Ch. Lux-Steiner**
*Professor at the Institute of Heterogeneous Materials Systems*

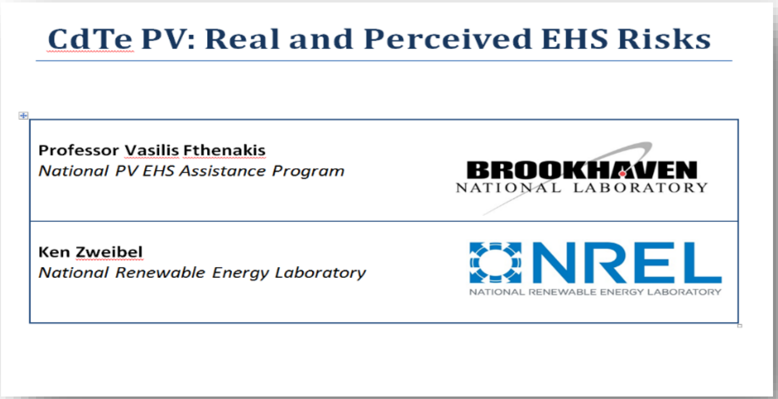
**Jürgen Werner**
*Professor at the Photovoltaic Institute (IPE)*

**Thomas B. Johansson**
*Professor at the International Institute for Industrial Environmental Economics*

**"The emissions produced during the life-cycle** of the modules **are extremely low**, and **large-scale use of CdTe Photovoltaic modules does not present any risks to public health and the environment."** Specifically it was found that:

1. CdTe PV modules have **shorter energy payback times and lower life cycle CO2 emissions than any other PV systems**, e.g. crystalline silicon (c-Si) or CIGS
2. Cd is produced as a by-product of Zinc production and can either be put to beneficial uses or be sequestered and stored in a way that won't allow for any releases into the environment. **CdTe used in PV is in an environmental stable form** that doesn't leak into the environment during normal use or foreseeable accidents and therefore **can be considered the environmental safest current use of cadmium**
3. **Air emissions of cadmium (Cd)** from the whole life-cycle of CdTe PV **are 100-360 times lower than Cd** emitted into air routinely from **coal and oil power plants**
4. The **potential accidental emissions** occurring during fires are **five orders of magnitude lower** than routine emissions during the operation of **coal and oil power plants**
5. **By investing in recycling, First Solar is** helping the whole industry by **setting up infrastructure that the whole industry will eventually need**

# U.S. NREL AND BROOKHAVEN STUDY (2003): EXECUTIVE SUMMARY


CdTe PV: Real and Perceived EHS Risks

Professor Vasilis Fthenakis
*National PV EHS Assistance Program*

BROOKHAVEN NATIONAL LABORATORY

Ken Zweibel
*National Renewable Energy Laboratory*

NREL NATIONAL RENEWABLE ENERGY LABORATORY

"The **environmental risks from CdTe PV are minimal**" and replacing coal generation with PV "will **prevent Cd emissions** in addition to preventing **large quantities of $CO_2$, $SO_2$, $NO_x$, and particulate emissions**." Specifically it was found that:

- CdTe is a **more stable and less soluble** compound than Cd…
- The vapor pressure of CdTe at ambient conditions is zero. Therefore, it is **impossible for any vapors or dust to be generated** when using PV modules.
- Substantial quantities of **cadmium is generated as a by-product** [of zinc production], no matter how much Cd is used in PV… **Encapsulating cadmium as CdTe in PV modules presents a safer use** than its current uses and is **much preferred to disposing it.**
- Results of **years of biomonitoring have shown** that there are **no significant observed increases in levels of worker exposure** [to cadmium compounds in PV manufacturing facilities]
- A typical U.S. coal-power plant emits about 1000 tons of CO2, 8 tons of SO2, 3 tons of NOx, and 0.4 tons of particulates per GWh of electricity produced. **All these emissions will be avoided when PV replaces coal…**
- CdTe PV end-of-life or broken modules **pass Federal (TCLP-RCRA) leaching criteria for non-hazardous waste.** Therefore…modules could be disposed of in landfills.
- The **issue of recycling is not unique to CdTe**. The **disposal of current x-Si modules**, most of which **incorporate Pb-based solder, presents similar concerns.** Recycling the modules at the end of their useful life completely resolves any environmental concerns.

# Assessment of the Risks Associated with Thin Film Solar Panel Technology

Submitted to

**First Solar**

by

**The Virginia Center for Coal and Energy Research**
Virginia Tech

8 March 2019
Blacksburg, Virginia, USA

# VIRGINIA CENTER FOR COAL AND ENERGY RESEARCH

*www.energy.vt.edu*

The Virginia Center for Coal and Energy Research (VCCER) was created by an Act of the Virginia General Assembly on March 30, 1977, as an interdisciplinary study, research, information and resource facility for the Commonwealth of Virginia. In July of that year, a directive approved by the Virginia Polytechnic Institute and State University (Virginia Tech) Board of Visitors placed the VCCER under the University Provost because of its intercollegiate character, and because the Center's mandate encompasses the three missions of the University: instruction, research and extension. Derived from its legislative mandate and years of experience, the mission of the VCCER involves five primary functions:

- Research in interdisciplinary energy and coal-related issues of interest to the Commonwealth
- Coordination of coal and energy research at Virginia Tech
- Dissemination of coal and energy research information and data to users in the Commonwealth
- Examination of socio-economic implications related to energy and coal development and associated environmental impacts
- Assistance to the Commonwealth of Virginia in implementing the Commonwealth's energy plan

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The work reported herein was performed and managed independently by VCCER. The assessments and opinions expressed are those of the authors.

## Acknowledgments

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# 1 Summary

This report reviews the environmental risk profile of utility-scale cadmium telluride (CdTe) photovoltaic installations with relevant information from the scientific literature and an audit of the manufacturing and recycling facilities of a domestic manufacturer. Current photovoltaic technologies are described, and the environmental and health issues associated with CdTe are identified. Solubility measurements, bioavailability, acute aquatic toxicity, oral and inhalation toxicity, and mutagenicity studies all confirm CdTe has different physical, chemical, and toxicological properties than Cd. The CdTe compound is less leachable and less toxic than elemental Cd. The risks to the environment arising from broken solar panels during adverse events are considered by reviewing experimental results, theoretical worst-case modeling, and observational data from historical events. In each case considered, the potential negative health and safety impacts of utility-scale photovoltaic installations are low. The need for end-of-life management of solar panels is highlighted in the context of recycling to recover valuable and environmentally sensitive materials. Based upon the potential environmental health and safety impacts of CdTe photovoltaic installations across their life cycle, it is concluded they pose little to no risk under normal operating conditions and foreseeable accidents such as fire, breakage, and extreme weather events like tornadoes and hurricanes.

# 2 Background

The *2018 Virginia Energy Plan*, required under Virginia Code § 67-201, was released by Governor Northam on October 2, 2018. The plan emphasizes that the legislature has supported:

- 5,000 megawatts (MW) of utility-owned and utility-operated wind and solar resources deemed in the public interest
- 500 MW of rooftop solar resources that are less than 1 MW in size deemed in the public interest
- $1.1 billion investment in energy efficiency programs by investor-owned utilities, and
- Cost recovery structures for projects that modernize the grid and support the integration of distributed energy resources.

The Plan also noted: "Given the economic development opportunities in the solar sector, solar energy has significant room to grow in the coming years. The Solar Energy Industries Association projects that solar energy will grow by an additional 2,293 MW over the next five years."

The Plan also discussed commitments to utility-scale and distributed solar resources and recommended that: "Governor Northam should double the Commonwealth's 8 percent renewable energy procurement target to 16% by the end of 2022. This target would facilitate the construction of an additional 110 MW of utility-scale and distributed renewable energy resources. In accomplishment of this target, the Commonwealth should complete both on-site PPAs and off-site utility-scale solar and wind projects."

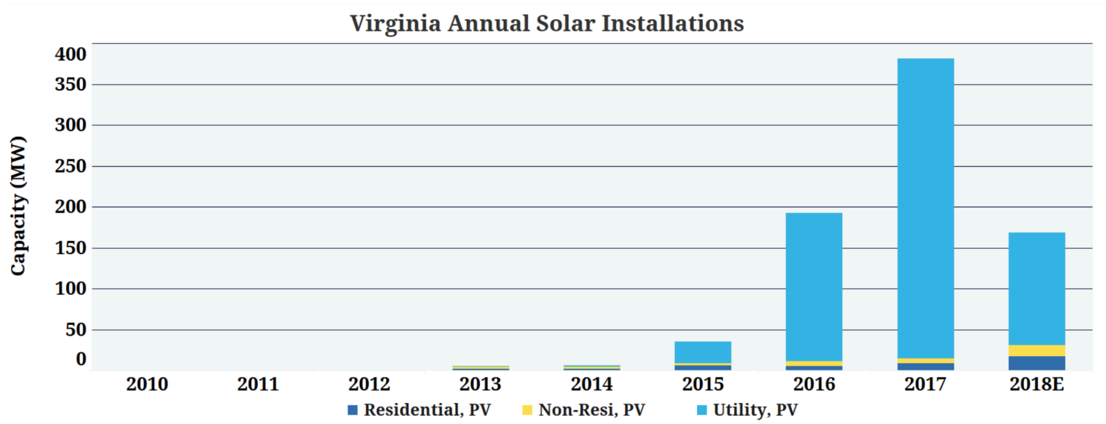


Figure 1: Virginia photovoltaic installation forecast [1].

Since utility-scale photovoltaic installations (solar facilities) are a relatively new component of Virginia's energy infrastructure (Figure 1), the public needs to be informed about potential impacts of the technology on communities. Multiple economic and technological factors must be considered to design and build a solar facility. The case for selecting a particular electric generation technology is usually made with a technique called life-cycle assessment. The technique considers environmental impacts associated with the "cradle-to-grave" stages of a power facility's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

A life-cycle assessment compiles a list of the energy and material inputs used in the life of the power generation facility, considers releases of materials that affect the environment, and evaluates the potential costs associated with the inputs and releases. Life-cycle assessments are sensitive to assumptions built into the underlying model, but they can help incorporate indirect costs into the planning and design of a facility. When considering electrical energy generation, life-cycle assessments for non-fossil fuel based energy sources — such as nuclear, wind, solar, hydro-power — tend to have lower impacts from factors such as greenhouse gases, fine particulates, and eutrophication (harmful enrichment of nutrients to water bodies), but they exert environmental pressure through factors like land occupation, and demand for materials in limited supply [2, 3, 4, 5, 6, 7, 8, 9].

## 2.1 Purpose and Scope

This report reviews available risk assessments for cadmium telluride (CdTe) semiconductor materials used in the construction of thin film photovoltaic solar technology under consideration for Virginia solar facilities. The review is based upon a survey of technical literature and an audit of the manufacturing and recycling facilities of one domestic manufacturer of CdTe solar panels.

## 2.2 Photovoltaic Technologies

Technologies for converting solar energy directly into electrical energy, called photovoltaic or PV systems, have evolved rapidly over the past several decades. Commercial photovoltaic systems developed over this period may be grouped into three categories. First generation photovoltaics rely on crystalline silicon (c-Si) in either a single crystal or polycrystalline form to convert solar radiation to electric current. Second generation photovoltaics employ a thin film material such as amorphous silicon (a-Si), multi-junction amorphous and polycrystalline silicon, cadmium telluride (CdTe), copper indium diselenide or disulphide (CIS), or copper indium gallium diselenide/disulphide (CIGS) to do the energy conversion. Third generation photovoltaics add solar concentrators and trackers to the system and may use other semiconductor materials for the conversion process [4]. Each technology has specific strengths and weaknesses, and the overall driver behind all these technologies is the need to reduce the energy cost for consumers. The energy return is often couched in terms of parameters like the "energy payback time," which represents the time needed for a particular technology to produce the energy used to manufacture, install, operate, and decommission it [4].

Weather also plays an important role in the economy of photovoltaic technologies. Solar insolation (a measure of solar strength), temperature, and relative humidity are weather-related factors that impact the energy production of a solar facility. Insolation affects the amount of primary energy available for conversion to electricity, temperature influences the conversion efficiency of the photovoltaic semiconductor, and humidity affects the energy spectrum that falls on the solar panels. The solar insolation for Virginia is roughly halfway between the low values found in the northeast United States and the peak values found in the deserts of the American southwest. Virginia's temperature and humidity are both fairly high. Given these weather-related factors, the leading utility-scale photovoltaic technology is arguably thin film CdTe photovoltaics [10]. For this reason, the remainder of this report will focus on this technology.

# 3 CdTe Thin Film Photovoltaics

The upper portion of Figure 2 shows an array of CdTe thin film photovoltaic modules on fixed mounts. The number of panels in the array determines the energy generating capacity of the system. The lower portion of Figure 2 is a schematic cross-section through a CdTe photovoltaic module illustrating its internal layers. The central CdTe semiconductor layer is quite thin, as can be seen from the size comparison in the figure between the CdTe film thickness and the thickness of human hair, a blood cell, and the semiconductor layer of silicon photovoltaic devices. The front and back of a CdTe photovoltaic module are glass sheets that transmit the incoming light and protect the internal components. The internal layers provide a semiconductor junction that converts solar radiation to electrical energy and conduction paths to collect the electrical current and connect it to external circuitry.

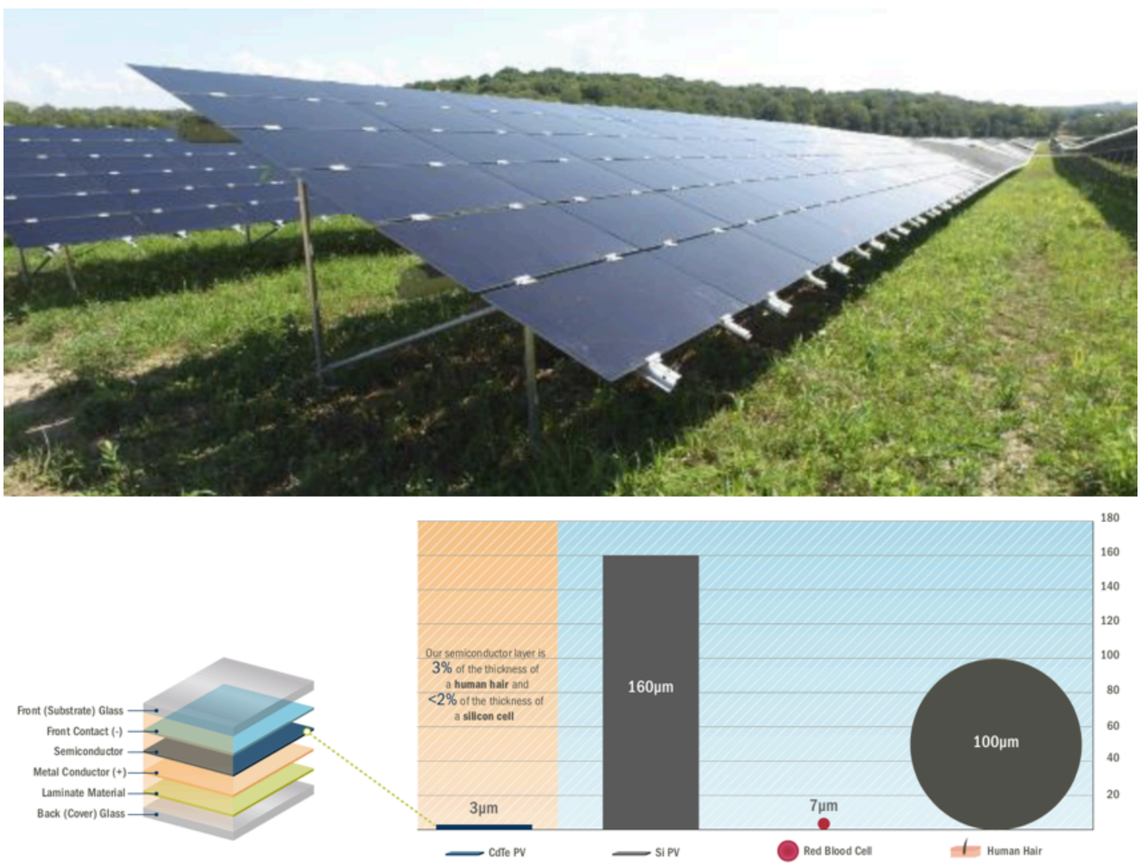


Figure 2: A CdTe photovoltaic system (top), and a schematic cross-section of a CdTe photovoltaic module (bottom). For comparison, the central CdTe layer is thinner than the thickness of the corresponding semiconductor layer in a silicon photovoltaic device, or the diameter of a red blood cell, or the thickness of human hair. Image source: First Solar, Inc.

## 3.1 Environmental and Health Issues

Some stakeholders have raised environmental and health concerns with thin film photovoltaic installations because of the use of cadmium compounds in the semiconductor thin film. Cadmium (Cd) is a heavy metal that has adverse effects on human health [11]. Cadmium occurs naturally in soil; the average concentration in Virginia soils is 0.15 mg of Cd/kg soil [12]. Common contributors of cadmium to the environment from human activity are the combustion of coal for power generation and the application of commercial fertilizers for agriculture. Human exposure to cadmium is higher for smokers than non-smokers [13]. Once dissolved in water, Cd can be incorporated into the tissue of crop plants [14] and make its way into the food chain.

Given the potential impact it poses on crops, one approach to assessing environmental hazards of Cd is to estimate the extent to which Cd contamination increases the Cd concentration of soil. For example, this strategy has been used to estimate that the Cd expelled during combustion at a 3000 MW coal-fired power plant deposits 0.00002 mg of Cd/kg soil over the land adjacent to the power plant [15]. A similar approach has been used to show that fertilizing soil with Cd-rich municipal sewage sludge may increase the Cd content of soil by 10 to 15% [12].

In analogous fashion, a simple mass balance (that ignores chemical differences between CdTe and Cd) suggests extracting the Cd contained in a typical CdTe thin film photovoltaic module and mixing it with the underlying soil could increase the concentration of Cd by an amount similar to that expected from fertilizing with municipal sludge. However, using this approach to assess the environmental risk from photovoltaic systems of CdTe is fundamentally flawed for two reasons: (1) it treats the toxicity of cadmium telluride as equivalent to that of cadmium without recognizing the significant chemical differences between the two [16, 17], and (2) it misrepresents the ways in which CdTe photovoltaic solar panels interact with the environment [18].

First, the environmental risks of CdTe and Cd cannot be assumed to be equivalent because the two substances are not chemically interchangeable. To draw a simple analogy, the properties of water ($H_2O$) are not similar to those of hydrogen gas ($H_2$) just because the two species both contain hydrogen. Just as it is improper to assume water can burn because hydrogen burns, it is invalid to treat CdTe as if it were as toxic as Cd.

The chemical difference between cadmium telluride and cadmium is partially reflected in their different physical properties. Cadmium telluride has a high melting point (1092°C) relative to that of elemental cadmium (324°C) and tellurium (449°C) [16]. The much higher melting point of CdTe reflects a strong chemical affinity of Cd for Te (bond strength $> 5$ eV) and the chemical stability of this compound [16]. In qualitative terms, cadmium and tellurium bind strongly to each other, so the cadmium in a CdTe molecule is less chemically available to react with other chemical species. For this reason, the toxicity of CdTe is expected to be different from that of elemental Cd, and CdTe also may have very different accessibility to the environment than Cd. These qualitative interpretations are borne out by experiments. Solubility measurements, bioavailability, acute aquatic toxicity, oral and inhalation toxicity, and mutagenicity studies all confirm CdTe is considerably less toxic than Cd [19, 20].

Second, with regard to the way CdTe interacts with the environment, a life-cycle analysis of CdTe photovoltaics with a focus on capturing cadmium flows and cadmium emissions into the environment [18, 21] compared the 'input' of cadmium to the environment from the CdTe photovoltaic life-cycle with the inputs from a variety of other Cd sources including coal-fired power plants and Ni-Cd batteries. A significant proportion of all Cd released to the environment comes from the emissions of zinc smelting (Cd is produced as a byproduct of zinc refining). This Cd release arises regardless of whether or not it is used in an application.

In photovoltaic module manufacturing, life cycle emissions of heavy metals are primarily associated with indirect emissions from fossil fuel electricity consumption [21]. The actual manufacturing process for CdTe photovoltaic modules directly releases a negligible amount of Cd to the environment because the electrodeposition or vapor transport processes used to produce CdTe thin films require high-purity conditions and tight industrial control. All the Cd consumed in the production of CdTe thin films either ends up in the deposited film or it is recycled. The aforementioned life-cycle analyses [18, 21] also noted Cd is not released during the normal operation of photovoltaic modules. Aside from the potential of environmental CdTe release from damaged panels (considered in Section 3.3.1) or during panel decommissioning (considered in Section 4), the production of CdTe photovoltaic panels would have the consequence of *reducing* the net environmental release of Cd [22] because it diverts Cd from the waste stream of zinc refining operations to CdTe production which then reduces the amount of Cd that ends up in landfills [18].

## 3.2 CdTe Photovoltaic Module Testing and Reliability

As just noted, there is no risk of CdTe release to the environment as long as the photovoltaic modules are operating normally. The best way to ensure a CdTe photovoltaic system functions reliably is to start with a fault-tolerant design, use robust components, and evaluate system performance through frequent testing. Based upon an audit of First Solar's CdTe photovoltaic manufacturing facility in Perrysburg OH, these objectives can be achieved by using automated statistical process control throughout the entire production process [23]. A battery of electrical, static and dynamic loading, hail impact, thermal and humidity cycling, and light response tests are typically used to assess the reliability of manufactured panels [24]. Standardized tests are used to varying degrees by manufacturers across the photovoltaic industry and include UL 1703/IEC 61215/IEC 61730 certification testing, Long-Term Sequential Test, Atlas 25+ Certification, IEC 62804 Potential Induced Degradation-Resistant Certification, IEC 60068 Certification Desert Sand Resistance, and durability benchmarking by the Fraunhofer PV Durability Initiative.

At the system level, the quality of a utility-scale solar installation's electrical, mechanical, and energy yield can be certified by independent oversight agencies such as the VDE Testing and Certification Institute [25]. Many solar facilities also employ real-time tracking of energy yield with a granularity down to the level of a small number of connected panels. This level of monitoring makes it practical to identify photovoltaic panel failures and their location as soon as they occur. Real-time monitoring helps ensure panels that become damaged by adverse events like storms are located immediately and quickly repaired or taken out of service. This kind of pro-active monitoring is important to maintain the energy yield of an installation, but it also mitigates the environmental risk of CdTe release from broken modules.

## 3.3 Adverse Events

The approach used in this report to assess potential risks from adverse events is to review: (*i*) experimental results, (*ii*) theoretical worst-case modeling, and (*iii*) observational data from historical events.

### 3.3.1 Field Breakage

Several assessments of the risks associated with the leaching of CdTe from broken photovoltaic modules are available. There are data from experiments simulating the exposure of broken modules to rain, there is worst-case total release modeling, and there are studies of the loss of metals from shredded photovoltaic modules (crystalline silicon and thin film types).

The fate of CdTe in broken solar module pieces subjected to rainfall was tested by Steinberger [26], who found no critical increase in soil Cd concentrations after 1 year of leaching in an outdoor experiment with actual rainwater. Also, tests in Japan subjected modules with 1 to 5 cracks to a quantity of simulated acid rain (pH 5) equivalent to 40 days of average rainfall; these experiments produced elution concentrations below Cd drainage and waste criteria [27].

In worst-case total release modeling, the extent of Cd leaching from broken CdTe modules in rainwater has been explored under different scenarios [28], and Cd concentrations were predicted to fall well below conservative human health screening levels [28].

A study by Tammaro [29] demonstrated that tumbling shredded photovoltaic modules in water for a day caused water to pick up detectable concentrations of most of the metals found in the original solar panels (Al, Pb, Sb, Ag, Cd from crystalline silicon solar panels and Al, Cr, Cd, Te, Se, Cu, Pb from thin film solar panels). However, it is not clear how the leaching behavior of a tumbled aggregate of centimeter-sized pieces relates to solar panels broken in service.

When photovoltaic modules break in the field, they crack but remain intact. Encapsulation of the module components is achieved through the use of a glass-laminate-glass design (Figure 2). The encapsulation bond strength is on the order of $\sim 50$ kg/cm$^2$ making it very difficult to separate the front and back of the module. For example, in a landfill experiment, photovoltaic modules were crushed with six passes by a landfill compactor with a contact load of 50 tons, and the crushed module pieces maintained the front-back encapsulation [30].

Furthermore, under the normal operation of a solar facility, system performance monitoring and routine visual inspection ensures non-functioning modules are detected and promptly removed from the field [31], so even when breakage occurs, long-term exposure to rain is not a likely scenario. Nevertheless, the leaching of a variety of metals from shredded panels [29] demonstrates the need for responsible end-of-life management for all solar technologies (see Section 4 below).

### 3.3.2 Fires

The fate of CdTe in solar modules subjected to a fire was tested by Fthenakis et al. [32]. By heating sections of a double-glass CdTe solar module to 1100°C, these investigators simulated degradation of a solar panel on the roof of a burning building (a building fire can reach higher temperatures than those expected around ground-mounted modules in a grass or brush fire). The simulated building fire softened the front and back glass panels which quickly joined and encapsulated the CdTe thin film. The glass essentially sealed all the CdTe, and prevented it from volatilizing and escaping.

Using a different approach that assumes total release of more than four times the amount of CdTe contained in today's modules, a large fire area, and the shortest distance from the emission site, the Bavarian Environmental Protection Agency used a computational method with an analytical model to conclude, "the distribution calculations carried out show that, from a technical standpoint, a serious danger for the immediate neighborhood and general public can certainly be excluded when modules containing CdTe burn" [33]. Thus, the fate of CdTe in photovoltaic modules in simulated fires and the predicted dispersal of CdTe by analytical models suggest CdTe cleanup following a fire should be straightforward with standard methods.

### 3.3.3 Storms

Experience with severe storms suggest solar facilities are relatively resilient against high winds and flooding. The following events provide case studies of storm-induced damage to CdTe photovoltaic installations and storm related environmental risks.

**April 2015** A tornado struck the Desert Sunlight Solar Farm in the Mojave Desert of California. Of the installation's 8,800,000 photovoltaic modules, 154,843 modules were damaged by the tornado (1.8%). The damaged panels were collected, approximately 135,000 were recycled, and the remainder were disposed of. Sampling of soil and module pieces from the tornado event passed Toxicity Characteristic Leaching Procedure tests, and an environmental non-governmental agency contacted the U.S. Bureau of Land Management and reported no indication of soil contamination. *Link: Desert Sunlight Tornado Damage*.

**September 2017** Hurricane Maria (category 5, maximum wind speed of 175 mph) struck the Sonnedix Horizon facility (Salinas Solar Park) in Puerto Rico and caused minor damage to the photovoltaic modules. Of the installation's 167,832 modules, only 872 were damaged (0.52%). *Link: Status Report After Hurricane Maria*.

**September 2018** Hurricane Florence (category 4, maximum wind speed of 130 mph) struck the Carolinas causing minimal damage to the solar facilities of Duke Energy and Strata Solar, the two largest solar power operators in North Carolina, with over 20 facilities utilizing CdTe photovoltaics. Only one site experienced wind damage: 12 modules were damaged out of a total of more than 600,000 modules (0.002%). *Link: Minimal Damage After Hurricane Florence*.

**October 2018** Hurricane Michael (category 4) struck Florida causing no damage to the solar facility of GameChange Solar in Tallahassee FL. *Link: GameChange Solar Systems Emerge Unscathed from Hurricane Michael*.

Only a small number of modules were damaged in each of the hurricanes noted. Consequently, the documented hurricanes did not cause any release of CdTe to the environment. Damage from the California tornado in 2015 was more serious, but even with the larger number of broken panels, environmental tests demonstrated CdTe was not released into the environment.

# 4 End of Life Management

At the end of the 25 to 30 year service life of the solar panels in a utility-scale photovoltaic installation, a significant volume of solar panels must be decommissioned, disposed of, or recycled. It was recognized at least a decade ago that large solar facilities presented unique challenges and opportunities for recycling photovoltaic modules [34]. One challenge is that the semiconductor material, CdTe, is a very small fraction of a thin film photovoltaic module ($\sim$ 0.1% by weight), but it still must be extracted to provide raw material for future thin film photovoltaic module production. Because of the small quantity and low solubility of semiconductor material and the module encapsulation, the modules are characterized as federal non-hazardous waste at end-of-life using the Toxicity Characteristic Leaching Procedure [31].

Unlike spent consumer electronics and batteries which are small and widely distributed, utility-scale photovoltaic panels at the end of their service life are centrally located at solar facilities. This makes photovoltaic panel recycling a much more manageable problem than, for example, recovering and recycling Cd from Ni-Cd batteries [18]. Programs to collect used batteries have limited effectiveness, so it is difficult to recycle more than a modest fraction of spent batteries — the rest end up in landfills.

In addition to the relative ease of collecting modules from solar facilities, the simple construction of CdTe photovoltaic modules and limited number of components make it relatively straightforward to separate the materials for recycling. Industrial crushing and classification schemes separate the glass and metallic components so they can be re-manufactured. During recycling, the CdTe film is also extracted from the panel's glass substrate with chemical solvents (concentrated sulfuric acid and hydrogen peroxide) [35].

With current technology, over 90 percent of a CdTe photovoltaic power system is recyclable; that is roughly twice what is recoverable from consumer electronics such as laptops and desktop computers [36]. Recycling of decommissioned CdTe photovoltaic modules is now available on an industrial scale at several sites around the world, including in the United States. A proactive recycling plan for the modules can help ensure CdTe is available for use in future thin film photovoltaic module production. Recycling is important for all photovoltaic technologies to recover energy intensive, valuable, and environmentally sensitive materials.

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## Assessment of performance, environmental, health and safety aspects of First Solar's CdTe PV technology

| | |
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**Table 10** Water withdrawal results for ground-mounted CdTe PV systems. .......... 95

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AEGLs | Acute Exposure Guidelines |
| AM | Air Mass |
| ASTM | American Society for Testing and Materials |
| ASP | Average selling price |
| AZ | Arizona |
| BAM | *Bundesanstalt für Materialforschung und Prüfung* |
| BoS | Balance-of-System |
| CED | Cumulative Energy Demand |
| CIGS | Copper Indium Gallium Di-Selenide $Cu(In,Ga)Se_2$ |
| CSS | Closed-space Sublimation |
| CSIQ | Canadian Solar Inc. |
| CVD | Chemical Vapor deposition |
| CZTS | Copper Zinc Tin Sulfide |
| DEWA | Dubai Electricity & Water Authority |
| DRAS | Delisting Risk Assessment Software |
| EC | European Commission |
| ECHA | European Chemicals Agency |
| EH&S | Environmental, Health and Safety |
| ENTSOE | European Network for Transmission System Operators for Electricity |
| EoL | End-of-Life |
| EOLR | End of Life Recycling |
| EPA | US Environmental Protection Agency |
| EPBT | Energy Pay-Back Time |
| EPC | Engineering Procurement and Construction |
| EROI | Energy Return on Investment |
| ERPG | Emergency Response Planning Guidelines |
| EU | European Union |
| EVA | Ethyl-vinyl Acetate |
| FMEA | Failure Mode and Effects Analysis |
| FS/FSLR | First Solar Inc. |
| GHG | Greenhouse Gas |
| GTM | GTM Research |
| GWP | Global Warming Potential |
| HEPA | High Efficiency Particulate Air |
| HQCL | Hanwha Q.CELLS |
| ICP | Inductively Coupled Plasma |
| IEA PVPS | International Energy Agency's Photovoltaic Power Systems Programme |
| IEC | International Electrotechnical Commission |
| IR | Infrared |
| Irr | Irradiation |

| | |
|---|---|
| JASO | JA Solar |
| JKS | Jinko Solar |
| LC | Lethal Concentration |
| LCA | Life Cycle Assessment |
| LCoE | Levelized Cost of Energy |
| LD | Lethal Dose |
| LID | Light Induced Degradation |
| LR | Learning Curve |
| MENA | Middle East and North Africa |
| m-Si/mc-Si | multi-crystalline silicon |
| NEA | Net Energy Analysis |
| NEG | Net Energy Gain |
| NMOT | Nominal Module Operating Temperature |
| NREL | US National Renewables Energy Laboratory |
| O&M | Operation and Maintenance |
| OEL | Occupational Exposure Limit |
| OH | Ohio |
| OSHA | Occupational Health and Safety Administration |
| PER | Predicted Energy Ratio |
| PID | Potential Induced Degradation |
| POI | Point of Interconnection |
| PR | Performance Ratio |
| PV | Photovoltaics |
| Q/A | Questions and Answers |
| QT | Quality Test |
| R&D | Research and Development |
| R.H. | Relative Humidity |
| RC | Recycled Content |
| RCOL | Reverse Current Overload |
| RSA | Recycling Service Agreement |
| sc-Si | single -crystalline silicon |
| SF | Spectral Factor |
| SQ | Shockley-Queisser |
| STC | Standard Test Conditions |
| STLC | Soluble Threshold Limit Concentration |
| STP | Suntech Power Holdings |
| TCLP | Toxicity Characteristic Leaching Procedure |
| TCO | Transparent Conductive Oxide |
| TOF | Time-of-Flight (TOFSIMS stands for Time-of-Flight Secondary Ion Mass) |
| TSL | Trina Solar Limited |
| UAE | United Arab Emirates |
| UL | Underwriter Laboratories |

| | |
|---|---|
| UNEP | United Nations Environment Programme |
| USA/U.S. | United States of America |
| USEPA | United States Environmental Protection Agency |
| UV | Ultraviolet |
| VLS | Very Large Scale |
| VTD | Vapor Transfer Deposition |
| WECC | Western Electricity Coordinating Council |
| WEEE | Waste Electrical and Electronic Equipment |
| WET | Waste Extraction Test |
| WVTR | Water Vapor Transmission Rate |
| YGE | Yingly Green Energy |
| ZSW | *Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg* |

# 1.- EXECUTIVE SUMMARY

First Solar has previously conducted 14 peer review studies regarding its CdTe PV module technology, with a strong focus on the environmental, health, and safety aspects. To that end, independent specialists from Brazil, Chile, China, the European Commission (Joint Research Centre), France, Germany, India, Japan, the Middle East, South Africa, Spain, Thailand and the USA have been invited to participate.

The present peer review has been carried out by specialists from Fraunhofer CSP (Germany), CNRS (France) and Oxford Brookes University (England) in a joint project coordinated by CENER (Spain).

The purpose of the present joint work is to review and evaluate, from an independent point of view, the performance and the environmental, health, and safety aspects of First Solar's CdTe PV technology. Although the report focuses on the European Union utility scale PV market, some aspects of the review are more broadly applicable.

The methodology applied for working out the present report is based on a thorough data mining of publicly available sources. Articles and reports published by recognized scientists, international agencies and research and development institutions have been reviewed, as well as confidential information provided by First Solar on their specific technology and management procedures. The information has been subjected to a critical analysis, based on the experience and know-how of the experts participating in this peer review. In addition, the experts from each institution visited First Solar's facility in Perrysburg (USA) and met with key plant staff and corporate management. In that visit, several presentations with confidential information were shared and discussed. This information exchange provided an in-situ scrutiny to address key technical questions and procedures of environmental, health, and safety aspects of the manufacturing and recycling processes, as well as the waste management systems to supplement data in publications. The main findings and conclusions extracted from the literature review and the site visit are summarized in the following paragraphs.

First Solar's thin-film CdTe PV technology accomplished a remarkable increase in cell efficiency of about 5 percentage points in 5 years, from 17.3% to the 22.1% achieved in 2015. In the mid-term, First Solar's technology roadmap has a goal of 24% cell efficiency that is projected to render 19% efficiency at module level. First Solar's PV modules are produced according to advanced standards with respect to product lifetime, reliability, quality and performance as documented in this report.  An elaborate quality control and reliability testing program is maintained close to production and reliability testing outdoors is also available at various test sites representing different climatic conditions from arid to hot and humid. Long-term field performance monitoring programs have led to valuable data and know-how on manufacturing PV modules with extended lifetime. First Solar is active in the complete value chain of CdTe PV technology adding valuable benefits with their developments and improvements in the utility-scale PV power plant monitoring and performance analysis, operations and maintenance activities, and grid integration aspects.

High volume and low cost manufacturing enables the large-scale deployment of PV technologies, which drive down the levelized cost of energy (LCoE). The evaluation of PV technologies should be based on life cycle assessment (LCA) and should also take into account socio-economic benefits. In that respect, it has been found that CdTe PV technology is in a leading position with respect to many environmental parameters among all PV technologies. Also, on the basis of a given cumulative production, the price of CdTe modules is currently lower by a factor of 4 to 5 compared to silicon-based PV. Strictly reasoning with the mechanism of price reduction by scale effect, this means that CdTe technology is inherently less expensive than silicon-based technologies, with the reason being the simpler production process of thin film technologies with less steps and the module produced at the same time of the cell.

In addition to exhibiting the lowest environmental impact amongst all PV technologies, CdTe PV technology also provides a safe and almost fully recyclable temporary sequestration route for the oversupply of raw Cd that is expected for the future, due to the increasing demand for Zn (of which Cd is an unavoidable by-product). Considering raw material availability from improved recovery from primary sources, and improvements in semiconductor intensity and recycling, in the long-term, Te availability does not represent a significant constraint. When taking into account the future large-scale deployment of CdTe PV, the only aspect of the life cycle environmental performance that has been identified to be a cause for some concern is the projected demand for copper, which is used in comparatively large quantities in the electrical part of the Balance-of-System, and therefore is not unique to CdTe PV. However, in the long-term, this concern is likely to be mitigated by the growing supply of secondary Cu derived from end-of-life recycling of decommissioned PV systems.

First Solar's manufacturing and recycling facilities are equipped with state-of-the-art technology to prevent, control and minimize emissions into the indoor and outdoor air. The facilities incorporate the necessary technology to treat waste effluents from all manufacturing operations, including modules recycling. Current local cadmium air emission and wastewater effluents are well below the local regulatory threshold limits. First Solar's Industrial Hygiene Management Program for Cd involves air sampling for personal area and equipment, as well as medical surveillance for employees, including blood and urine testing. Cadmium levels in indoor air are well below the occupational exposure limits. With regard to bio-monitoring tests, Cd levels in blood and urine demonstrate to be well below U.S. Occupational Health & Safety Administration criteria.

Under normal operation, First Solar's CdTe PV modules do not pose any environmental or health risk, since no emission of hazardous materials occurs. In case of foreseeable accidents, the risk to the public was reported to be low. In the event of a fire, utility scale PV power plants have limited on-site vegetation, with grass fires having short residence times and maximum temperatures below the melting point of CdTe. In the case of rooftop fires, the experimental fire testing results from Fthenakis *et al*., BAM, and CURRENTA confirm low air emission rates of Cd from CdTe PV modules during fire, and the calculations from the Bavarian Environmental Agency and Sinha *et al*. confirm that downwind Cd air concentrations are below acute exposure guideline levels. Because most of the Cd content is not emitted to air and remains in the module and module debris, it was recommended to accordingly dispose the contaminated residues and replace the soil, which is a normal procedure following building fires. Water used to extinguish the fires was reported to contain similar quantities of Cd assumed in a prior fate and transport study, which found insignificant impacts to soil and groundwater, where the latter could be confirmed with soil analysis. Peer-reviewed fate and transport investigations regarding leaching of broken or defective CdTe PV modules suggest that the potential risk is minimal based on worst-case modeling, experimental data, and O&M practices (routine inspections and power output monitoring) that detect and remove broken modules. Independent research, published in peer-reviewed scientific journals would contribute to support First Solar's experimental results. These scientific studies should include both, broken modules representative of field exposures and modules with integrity issues resembling possible situations encountered towards the end of life. For example, independent broken module leaching studies have historically been conducted by Fraunhofer Institute in Germany and NEDO in Japan on older generation CdTe PV modules with results below health and environmental screening limits.

Improper disposal and recycling as well as non-intended uses of CdTe PV modules is a controversial issue for the long-term deployment of CdTe PV technology. CdTe has a high chemical and thermal stability and is insoluble in water, which limits its leachability and bioavailability. The in-depth analysis of the available scientific documents suggests that the health risk associated with the disposal of CdTe PV modules in uncontrolled landfills is minimal at the present usage rates. More specifically, the screening level cumulative non-carcinogenic hazard index could exceed 1.0 only if the waste volume amounted to over 14 million modules over 20 years or over 5 million modules in 1 year (which would equal the disposal of an installation well above 500 MW peak in 1 year), assuming the disposal into a single, unlined landfill. The disposal of a multi 100 MW PV installation in a single uncontrolled landfill is already an upper bound case. Uncontrolled disposal of such a system is highly unlikely, considering that an installation of that size is a billion dollar investment, requiring extensive planning and impact assessment as well as construction and operating permits, which in all cases, foresee dismantling and disposal requirements.

High-value recycling (recovery of glass and semiconductor materials) is the ideal option for the end-of-life management of PV modules, including CdTe PV, but it must be entrusted to companies with the required knowledge and best environmental, health and safety practices, such as those being documented by CENELEC in support of the WEEE Directive (draft Standard EN50625-2-4). However, even in the case of informal recycling, unlike household consumer electronics, there would be few components in a monolithic thin film module valuable for being dismantled, aside from the junction box and cables.

First Solar is leading the PV industry in the establishment of collection and recycling programs that ensure the end-of-life recycling with a proven technology. In the EU, the inclusion of all PV technologies in the WEEE directive, which requires collection and recycling according to minimum standards, together with First Solar's recycling facility (in Frankfurt/Oder, Germany) enables the proper systems and policies to sustainably implement CdTe PV technology. Outside of the EU, First Solar's recycling services are globally available and implemented with recycling facilities in Perrysburg (USA) and Kulim (Malaysia), and adoption of that practice is based on competitive pricing.

From the life cycle analysis perspective, it is important to mention that if CdTe PV technology was deployed to displace conventional fossil fuel-based electricity generation, the benefits in terms of reduced greenhouse gas emissions would be between one and two orders of magnitude per kWh of produced electricity (a reduction from 600 g($CO_2$-eq) - 800 g($CO_2$-eq) to below 20 g($CO_2$-eq) per kWh).

Deploying CdTe PV in Europe would also decrease the overall Cd emissions per unit of generated electricity associated with thermal electricity producing plants.

In terms of total land transformation per unit of electricity generated, the performance of CdTe PV technology is several times better than that of other renewable technologies like wind, hydro and especially biomass, while it remains of the same order of magnitude as that of conventional technologies such as coal and nuclear power. Also, a key difference with respect to the latter technologies is that the type of land transformation caused by CdTe PV installations is much "lighter", and leads to much easier ecological restoration after decommissioning. In Europe, thermal electric power plants account for 40% of total water withdrawals, while CdTe PV technology requires little to no water during operation and has a much lower life cycle water demand compared to many alternative electricity generation technologies.

From most points of view, a large-scale deployment of CdTe PV technology would have positive long-term effects on the environment, and would not represent a health risk for the public during operation and foreseeable accidents. In the EU, policies are in place to safely recycle end-of-life modules, and First Solar's recycling facilities in Frankfurt/Oder (Germany) enable the responsible and sustainable management of CdTe PV technology at end of life. First Solar's recycling services are also globally available outside of the EU.

# 2.- TECHNICAL REPORT

Production of electricity by means of solar photovoltaic technology already provides a cost competitive solution in many countries around the world. In fact, the steady increases in efficiency and cost reduction of PV modules have allowed the achievement of grid parity in several countries. Photovoltaic solar electricity causes no emissions during the service lifetime and the sunlight supply is unlimited, guaranteed and free.

After three successive years of decline, the European PV market recovered last year in 2015 reaching nearly 100 GW of installed cumulative electricity generation capacity. In particular, photovoltaics already supply 4% to the European power mix, and it is estimated to have the potential to meet 8% of the electricity demand in 2020 and 15% in 2030. Photovoltaics will surely play a key role in achieving the target set by the European Commission of 20% of energy made up by renewable sources by 2020.

Although the initial PV technologies were based mainly on crystalline silicon as semiconductor, silicon is not the only semiconductor material that responds to sunlight for PV energy conversion. Other semiconductors have similar properties and First Solar's thin-film CdTe technology has demonstrated a remarkable advance, in the efficiency improvement but also in the reduction of costs, in the past years. In this regard, First Solar has demonstrated a technology capable of ranking in the top 10 manufacturers of PV modules in the last decade.

First Solar's frameless PV modules are formed by monolithically integrated CdTe semiconductor PV cells laminated between two glasses. The total semiconductor thickness is ≤3 microns and contains around 6 grams of Cd content (in the compound CdTe) per module. First Solar's Series 4 PV modules have an efficiency of 16.7% with a nominal power of 120 W. The company provides product warranties of up to 10 years and performance warranties of more than 80% of the initial power for 25 years. The company offers end-of-life recycling services through its industry-leading recycling program.

The present technical report is organized into four sections. A first introductory section, covering the main technological aspects of First Solar's CdTe PV module technology, will be presented comprising its technology and cost roadmaps. A section including quality management and field performance aspects of First Solar's CdTe PV technology for installation in European regions will follow. Next, environmental, health, and safety aspects of First Solar's CdTe PV module technology will be addressed, including First Solar's manufacturing procedures, which also comprise recycling activities. Moreover, normal operation of CdTe PV modules, also extending to non-intended uses and uncontrolled disposal will be investigated in this section. Finally, the energy and environmental impacts associated to CdTe PV systems, from the point of view of their whole life cycle performance will be addressed. Main environmental parameters will also be compared to other electricity generation sources. To finish, the main conclusions extracted from the present study are summarized in an additional section.

# 2.1.- FIRST SOLAR'S CdTe TECHNOLOGY AND COST ROADMAPS

CdTe solar cell technology represents one of the different photovoltaic technologies which are competing. According to the NREL chart,[1] there are 24 technologies under survey for record efficiencies at the laboratory cell level. They are classified under 5 groups, including one group on emerging technologies. However, coming to mainstream market only 2 groups are competing, one on wafer based silicon technologies (single and multicrystalline) and the other one on thin film technologies, with CdTe technology leading this group by market volume.

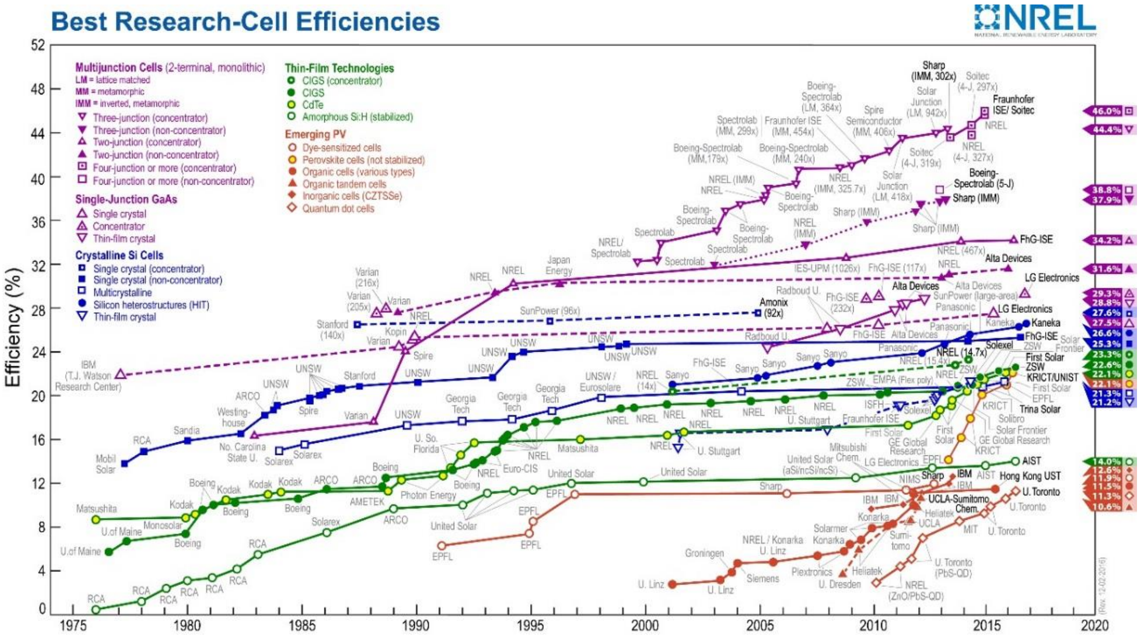



**Figure 1** Record efficiencies of PV Solar cells (from NREL as of 17th December 2016).

The aim of this section is to review the state of the art of the CdTe technology in this context with respect to efficiency and cost roadmaps. The efficiency roadmap is divided in two related subgroups, one concerns the record efficiency at the cell level, which represents the moving target, and the second one concerns the efficiency at the module level, which is the one relevant for market competitiveness. Some scientific aspects will be highlighted but without entering in too much details.

## 2.1.1.- EFFICIENCY ROADMAP

### 2.1.1.1.- Cell Development

The evolution of the record efficiencies of cadmium telluride solar cells is recalled in Figure 2[1,2]. Figure 2 provides more details about the recent evolutions related to record breaking steps. It shows a quasi-stagnation for about 20 years around 16%-17% efficiency, starting from the University of South Florida breakthrough in 1993 (15.8%) to the first record achieved by First

[1] www.nrel.gov/ncpv/images/efficiency_chart.jpg

[2] M. Gloeckler, "CdTe Solar Cell in 2016: Realization of the potential of CdTe thin-film PV", in *39th IEEE PVSC*, 2016.

Solar in 2011 (17.3%). During this period the opinion of many actors in the PV domain was that the cadmium telluride technology, in spite of its theoretical efficiency limit (at about 33%), had reached its “experimental practical limit”. The increase of 5% in the efficiency in 5 years, reaching a value of 22.1% in 2015, invalidates this opinion and provides a remarkable demonstration that the efficiency progress in CdTe technology was possible. To some extent, this type of evolution is also experienced for the other technologies, in particular crystalline silicon which was blocked around 25% for about 18 years. Only recently, new breakthroughs took place thanks to the progresses of a new technology, bringing the record at 26.6% (Kaneka, September 2016, Heterojunction + Back contacts). With 22.1% efficiency CdTe has overpassed polycrystalline silicon record cell by Trina (21.3% as shown in Figure 1) and is very close to that of CIGS solar cells (22.6% in 2016 at ZSW)[3]. This also demonstrates the ability of First Solar to anticipate the efficiency evolutions in 2013, predicting an achievable value of 22%[2]. This gives credibility to next goal of 24% efficiency at cell level, which is announced in the technological roadmap for mid-term (about 2019-2020 probably). It should be noted that this is in line with the efficiency objectives set for CIGS solar cells[4].

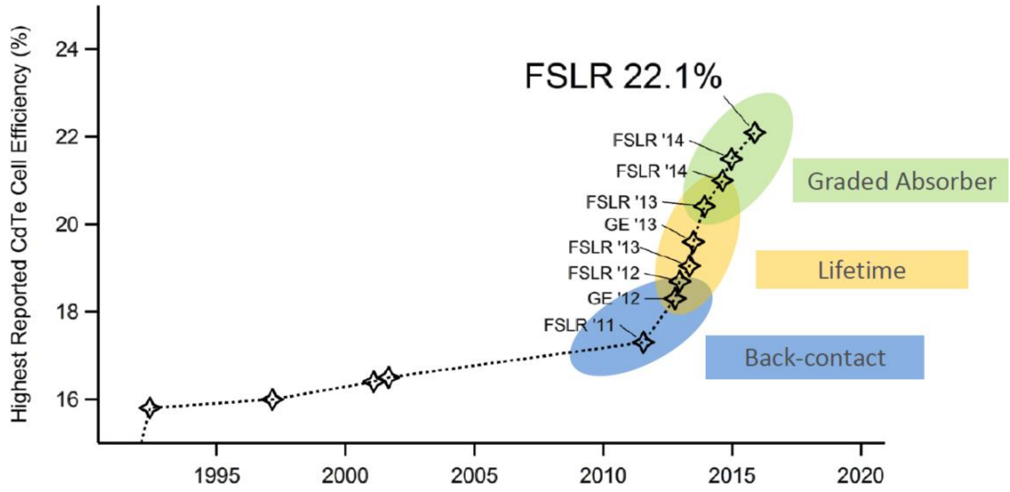



**Figure 2** CdTe record cell efficiency evolution.

The improvement in the efficiency is related to several breakthroughs in the technology of CdTe solar cells developed at First Solar in combination with contributions from General Electric which are now included in First Solar’s technology. This is a very good example of synergies between the two groups with respect to the CdTe technology. The breakthroughs concern three aspects as reported in reference [2]:

- The back contact
- The internal electronic life time
- The graded absorber

The back contact has been a severe issue in the field of CdTe technology for many years, with

[3] P. Jackson, *et al.*, “Effects of heavy alkali elements in Cu(In,Ga)Se2 solar cells with efficiencies up to 22.6%,” *Phys. Status Solidi RRL*, pp. 1–4, 2016.
[4] http://cigs-pv.net/wortpresse/wp-content/uploads/2015/12/CIGS-WhitePaper.pdf

a problem of non ohmic behavior and detrimental copper diffusion. It appears that these aspects have been solved by First Solar with the introduction of ZnTe buffer layer covered by a copper layer. Several recent scientific papers reported about the characterization of the ZnTe layer in controlling copper in CdTe[5]. The ZnTe layer also plays a role as a mirror for majority carriers in CdTe. Moreover, band gap alloying at the back contact is also possible with this material. This represents a key improvement as compared with previous technology.

The internal electronic lifetime is an optoelectronic property corresponding to the duration of excited electron hole pairs generated by the absorption of solar photons before being lost by recombination. It has to be distinguished from the module lifetime. The increase of the electronic lifetime in CdTe cells results from the optimization of the cadmium chloride treatment, leading to an efficient passivation of inner grain and grain boundaries in the CdTe layer. Chloride atoms tend to segregate at grain boundaries[6]. Thus, the lifetime measured by photoluminescence decay technique is about 100 ns, limiting the recombination processes within the CdTe layer. It is shown that increasing the lifetime in this range while increasing the doping level is a condition to achieve high efficiencies[7].

The graded absorber issue is probably the most impressive strategy introduced in First Solar's CdTe technology[2]. It has been a deliberate approach, which has proven to be a key factor for improvement in CIGS solar cells, but which was not studied specifically for CdTe. The idea is to create a lower band gap inside the CdTe layer which increases towards the interface with the front contact and with the back contact by means of alloying with other elements. It was known that such an effect was taking place between CdS and CdTe at the front contact, leading to inter-diffusion with the formation of a graded Cd(S,Te) layer at the interface. The first very positive role was to remove the abruptness of the 10% lattice mismatch between the two materials, with a graded lattice mismatch which resulted in reducing dramatically the density of recombination centers. The second one was to create a zone with a reduced band gap at the interface to the strong bowing effect of alloying. This provided a slight increase in the photocurrent density.

The breakthrough came from the same processes but with Se substitution instead of S, with the formation of a Cd(Se,Te) layer extending more deeper inside the CdTe layer and in the grain boundaries[2]. The system also presents a strong bowing effect, creating a gradient of the band gap with a minimum inside the absorber layer at about 1.35 eV. This allowed a fine tuning of the gradient and the front interface with superior quality as compared to the CdS/CdTe interface. This is a major reason of the improvement. The analysis of the device characteristics shows that the interface recombination is suppressed[2].

Grading with CdSe at the front interface has thus been a key breakthrough in the recent

[5] A. Colin *et al.,* "The roles of ZnTe buffer layers on CdTe solar cell performance*", Solar Energy Materials and Solar Cells, vol.* 147, pp. 203–210, 2016.
[6] C. Dan Mao *et al.*, "Measurement of Chlorine Concentrations at CdTe Grain Boundaries", *IEEE Journal of Photovoltaics*, 2014.
[7] A. Kanevce and T. Barnes, reported by M. Gloeckler, "CdTe Solar Cell in 2016, realization of the potential of CdTe thin film PV", *Oral presentation at IEEE PVSC*, 2016.

evolution of First Solar's CdTe technology. It allows the photocurrent collection to reach an unpreceded level of spectral responses with quantum efficiencies close to 90%, extending well towards the UV and the IR, thanks to a better charge collection in the CdTe and maybe in the Cd(Se,Te) layer (which was not the case with CdS) and a decrease in the band gap.

Theoretically, the ultimate efficiency of CdTe solar cells is about 33%, which translates into a practical efficiency of about 29% to 30%. It should be noted that GaAs single crystalline solar cells have already reached 28.8% efficiency[8], with about the same band gap as CdTe.

In the case of CdTe, recent theoretical studies have been carried out[7,9]. Figure 3 compares record efficiency cells for the three main technologies (m-Si, CIGS and CdTe) with the ideal Shockley Queisser limit (SQ)[9]. As can be appreciated from this figure, CdTe has already similar performance to m-Si.

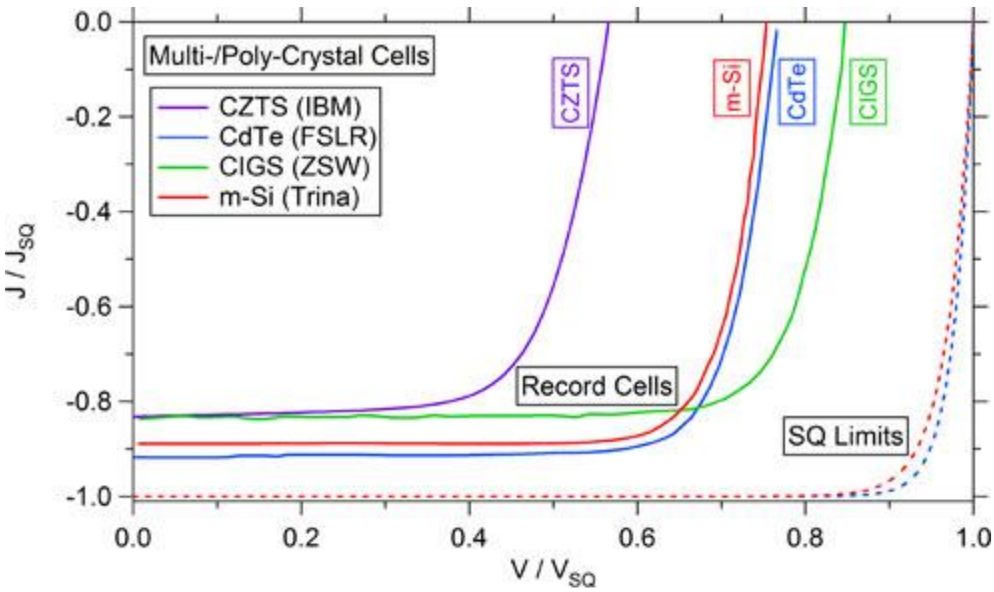



**Figure 3** Comparison of the I-V curves of record cell technologies (CIGS, CdTe and m-Si) with the ideal Shockley Queisser limit[9].

Moreover, the short circuit current could also be improved by the optimization of light trapping in the cell. The main limitation of CdTe technology comes from the open circuit voltage with a deficit of 25% with respect to SQ limit.

The analysis performed by First Solar of the progress to be done with regard to the open circuit voltage is shown in Figure 4.

[8] E. Yablonovitch *et al.*, "The optoelectronic physics that broke the efficiency limit in solar cells", *in IEEE Photovoltaic Specialist Conference (PVSC)*, 2012.
[9] M. Russell, *et al.*, "Status and Potential of CdTe Solar-Cell Efficiency", *in IEEE Journal of Photovoltaics,* vol. 5, no. 4, pp. 1217, July 2015.

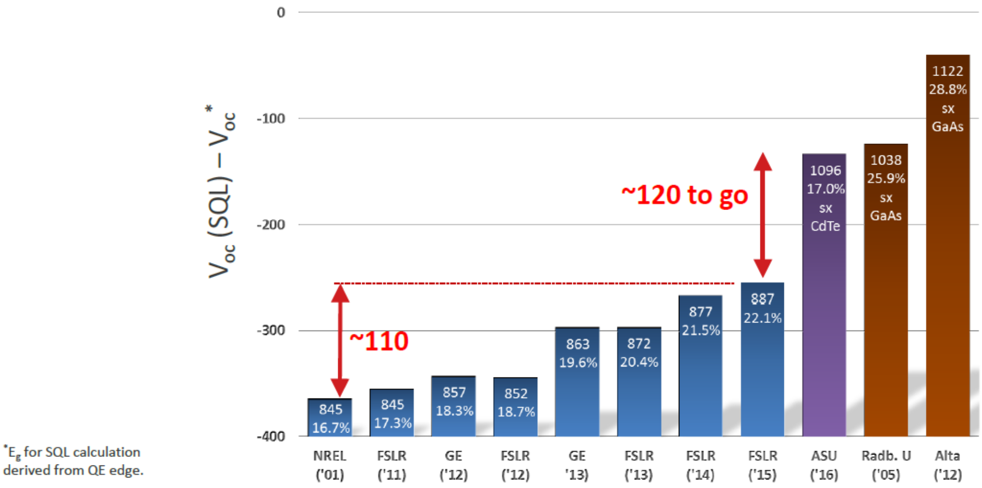



**Figure 4** Roadmap for open circuit voltage improvement in CdTe solar cells, expressed in mV and compared to reference devices, single crystal CdTe and GaAs devices. The Y value corresponds to the difference between the calculated theoretical open circuit voltage from the band gap value and that of the real device[2].

As can be appreciated from this figure, 110 mV have been gained from 2001 to 2015 and 120 mV can still be gained in the future by taking into account the recent results obtained on single crystal solar cells, with open circuit voltages of about 1.1 V demonstrated for both n[10] and p[11] type CdTe. It has to be mentioned that in the case of p type the results are obtained with phosphorus doping of CdTe, allowing a higher acceptor density (which is favorable to an increase of the open circuit voltage as compared to low doped CdTe in First Solar technology) and also an abrupt interface with a microcrystalline CdS layer. This cell architecture is different to that existing in First Solar's present cell technology where strong inter-diffusion of chemical elements at the interface between CdS(Se) and CdTe creates a graded interface and not an abrupt interface, which is found to be highly favorable to improve the conversion efficiency. This opens some questions regarding the choice of future strategies for increasing the open circuit voltage of First Solar cells. However, the authors of this study have made a lot of samples and the best results correspond to only a small fraction of the elaborated devices. Nevertheless, this shows that a significant margin exists to increase the open circuit voltage and that doping, as proposed by NREL[11] is a possible route.

The case of n type in obtaining high Voc is related to an excellent passivation effect due to alloying with magnesium to form (Cd,Mg)Te interface buffer layers[11]. This is clearly in accordance with the findings of First Solar with Se substitution.

From the previous analysis, it is concluded that routes exist for increasing the efficiency of First Solar's technology to about 24%, by playing with the increase of the open circuit voltage specifically. The work on single crystal and alternative deposition technologies, like CVD, is very useful for these prospects.

The longer term strategy for higher efficiencies, up to 27%, is based on improving further the

[10] Y. Zhao *et al.*, "Monocrystalline CdTe Solar Cells with open circuit voltage over 1 V and efficiency of 17%", *Nature Energy*, 2016. DOI 10.1038/2016.67.
[11] J.M. Burst *et al.*, "CdTe solar cells with open circuit voltage breaking the 1 V barrier", *Nature Energy*, vol.1, 2016.

CdTe single junction technology, dealing with the life time and doping level, in particular as shown in Figure 5[7].

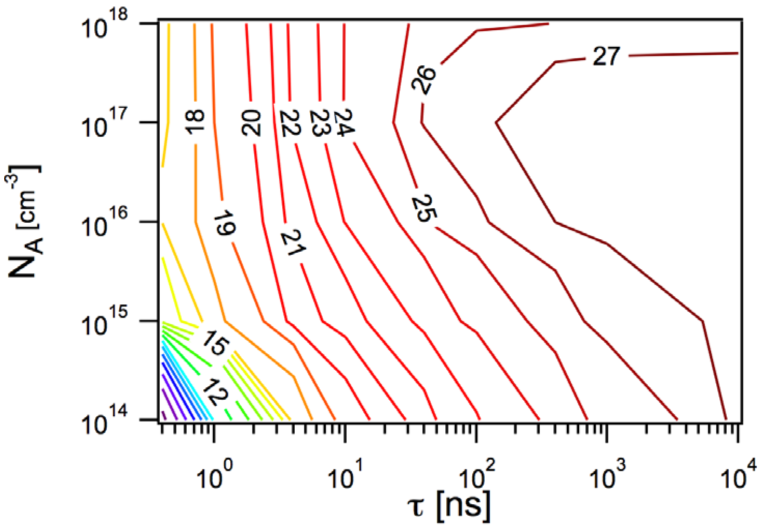


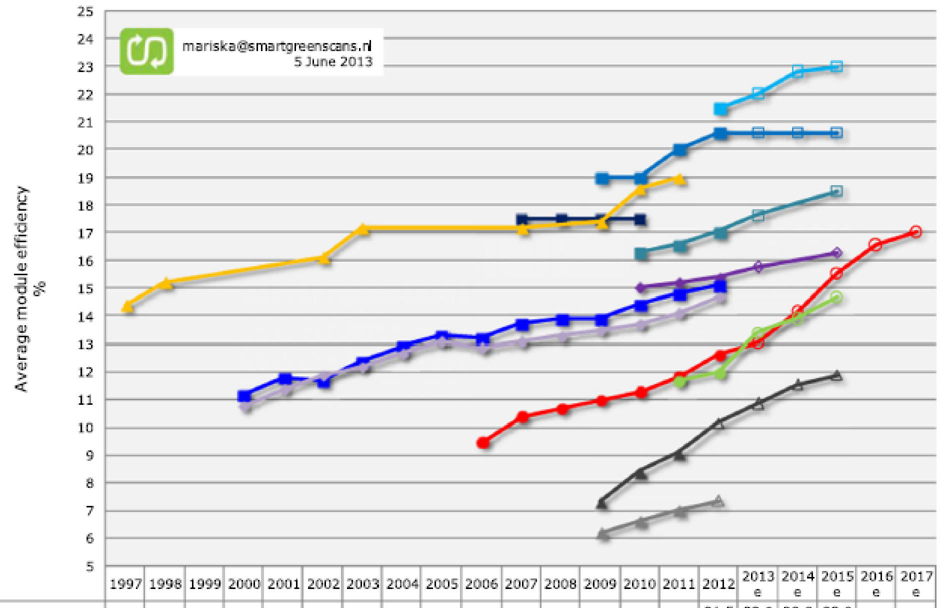

**Figure 5** Simulated contour plots of conversion efficiencies of CdTe solar cells versus bulk life time and acceptor doping level[7].

From the discussions during the Perrysburg site visit and the presentation, it appeared that the process to increase the efficiency of the cells is based on testing new ideas and making numerous experiments in well-defined conditions to address the effects on the basis of rigorous statistical analysis. This methodology, developed in the dedicated R&D laboratory, which is rather unique, allows step by step improvements on a solid basis and easy transfer to the pilot production line. This approach is associated to the deep usage of advanced in-house characterization techniques (structural, compositional, opto-electrical…) which brings a lot of information to discriminate the effects and to allow the process optimization.

#### 2.1.1.2.- Module developments

Analogous to the record efficiencies for laboratory cells, the comparison of the different PV technologies is made at the module level as shown in Figure 6[12].

[12] M.J. de Wild-Scholten, "Energy payback time and carbon footprint of commercial photovoltaic systems," *Solar Energy Materials & Solar Cells*, vol. 119, pp. 296–305, 2013.




| | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 e | 2014 e | 2015 e | 2016 e | 2017 e |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sunpower, X-series | | | | | | | | | | | | | | | | 21,5 | 22,0 | 22,8 | 23,0 | | |
| Sunpower, E-series | | | | | | | | | | | | | 19,0 | 19,0 | 20,0 | 20,6 | 20,6 | 20,6 | 20,6 | | |
| Sunpower, 1st generation | | | | | | | | | | | 17.5 | 17.5 | 17.5 | 17.5 | | | | | | | |
| HIT, Sanyo/Panasonic | 14.4 | 15.2 | | | | 16.1 | 17.2 | | | | 17.2 | | 17.4 | 18.6 | 19.0 | | | | | | |
| Mono-Si n-type PANDA, Yingli, CN | | | | | | | | | | | | | | 16,3 | 16,6 | 17,0 | 17,6 | | 18,5 | | |
| Multi-Si, Yingli, CN | | | | | | | | | | | | | | 15,0 | 15,2 | 15,4 | 15,7 | | 16,3 | | |
| Mono-Si (Photon Int Feb 2013) | | | | 11.2 | 11.8 | 11.7 | 12.4 | 12.9 | 13.3 | 13.2 | 13.7 | 13.9 | 13.9 | 14.4 | 14.8 | 15.1 | | | | | |
| Multi-Si (Photon Int Feb 2013) | | | | 10.8 | 11.4 | 11.9 | 12.2 | 12.7 | 13.1 | 12.9 | 13.1 | 13.3 | 13.5 | 13.7 | 14.1 | 14.7 | | | | | |
| CdTe, First Solar | | | | | | | | | | 9.5 | 10.4 | 10.7 | 11.0 | 11.3 | 11.9 | 12.7 | 13.1 | 14.2 | 15.6 | 16.6 | 17.1 |
| CIGS, Solar Frontier, JP | | | | | | | | | | | | | | | 11,7 | 12,0 | 13,4 | 13,9 | 14,7 | | |
| μc/a-Si, Oerlikon Solar Fabs | | | | | | | | | | | | | 7.4 | 8.4 | 9.1 | 10.2 | 10.9 | 11.6 | 11.9 | | |
| a-Si, TSolar, ES | | | | | | | | | | | | | 6.20 | 6.63 | 7.05 | 7.35 | | | | | |

**Figure 6** Historical roadmap average (real and estimated) total area module efficiency of commercial PV modules[12].

Data from years 2013 to 2017 were estimated values in this article from year 2013. In this regard, this study has been recently updated[13] and is shown in Figure 7.

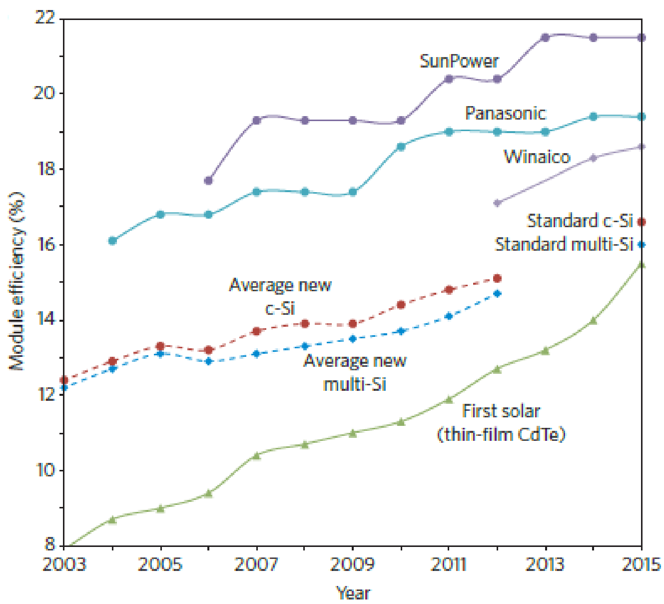



**Figure 7** Evolution of module energy conversion efficiencies as a function of the technologies.

[13] M. A. Green, "Commercial progress and challenges for photovoltaics," *Nature Energy*, vol. 1, pp. 1-4, 2016.

It appears that the progress of CdTe technology at the standard commercial module level has been faster than for silicon technologies and that in 2015 the level was approaching that of average crystalline silicon technologies (around 16%). This creates an increased competitiveness of CdTe technology with respect to silicon, especially the multicrystalline silicon technology.

Figure 8 gives a precise analysis of the status of First Solar module technologies in comparison with the module efficiencies sold by specific companies on the market (update Nov. 2015), prepared by ISE Fraunhofer[15], which confirms the above conclusions.

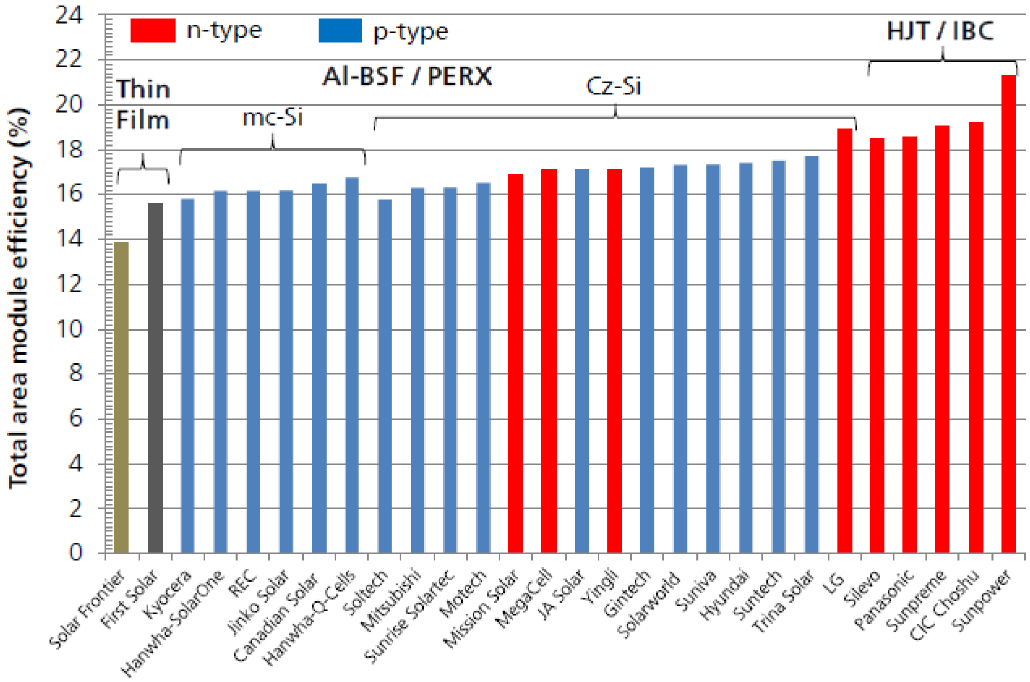



**Figure 8** Current efficiencies (as of November 2015) of selected commercial PV modules companies sorted by bulk material cell concept and efficiencies.

These values can be now compared with First Solar own releases shown in Figure 9, indicating 14.4 % in 2014 and 16.1% in 2015 for corresponding 14.1% and 15.5% extracted from Figure 7, which shows an agreement between both, while the values from First Solar are a bit higher (0.5%) because they are Q4 average instead of annual average.

One of the strengths of First Solar's technology and approach is the close relation between the R&D studies on cells performances and evolutions and the transfer to the module production. It is exemplified by the road map presented at the 2016 Analyst Meeting[14] (Figure 9).

[14] R. Garabedian, Technology Update, First Solar Analyst Day, 2016, available at: http://files.shareholder.com/downloads/FSLR/2968270837x0x884415/15EEFBFE-58CD-41E1-A505-8FCD0FAEE7B7/FS_AnalystDay_TechnologyUpdate.pdf

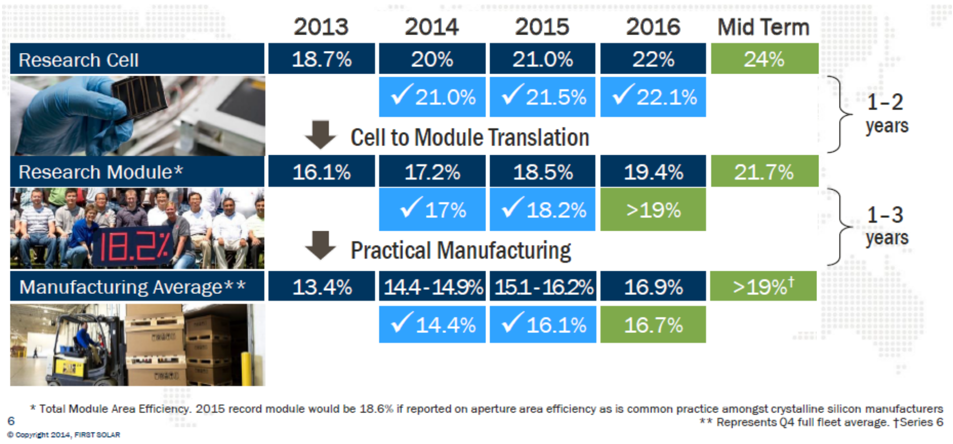



**Figure 9** Technological roadmap of First Solar from cells results objectives to module objectives[14].

The research cell objectives and results have been presented in the previous section. What appears in Figure 9 is the first step which aims to transfer the record cell results to a research module. This takes about one to two years. The 21.5% obtained in 2015 is already transferred to record research module value of 18.2% (total area corresponding to 18.6% active area). One can note that the absolute difference is about 3%, which is valid for previous year record too. Translating to the 2016 situation means that in 2017 the expected value of 19% should be obtained in research module. Then one to 3 years are needed to transfer the results to standard average production. The mean efficiency is further reduced by about 2% giving a present value of 16.1%. Thus, it takes between 2 and 5 years to transfer new cell technologies from R&D to standard module production.

The time between R&D and module production of 2 to 5 years represents a clear strength of First Solar's technology. The difference in efficiency of about 5% is comparable to what is found in other technologies. Nevertheless, reducing this gap further would be another source of competitiveness at the level of module production. At mid-term it is expected that the standard module efficiency would reach more than 19%.

### 2.1.2.- COST ROADMAP

#### Analysis from external sources

Figure 10 provides the price evolution of PV modules as a function of the cumulated production over the years in a log-log representation, often called the experience curve, for CdTe and crystalline silicon technology[15]. It appears also that today prices are similar between CdTe and Si technologies, confirming the competitiveness of CdTe technology at the price level, already pointed out for the conversion efficiencies in previous sections. Looking to the evolution, it appears that the data points for CdTe modules are almost translated as compared to the silicon one. This means that the two curves must be correlated via some market dependent phenomena. The evolution is usually fitted by a linear regression, giving a learning rate

[15] Fraunhofer, "Photovoltaics Report", November 2016, available at: https://www.ise.fraunhofer.de

coefficient (LR). Over the 35 past years the LR value for the global PV market is about 23% meaning that the price is decreasing by 23% when the production volume doubles. This allows extrapolating the price evolution to higher cumulated volumes. However, the LR coefficient can be determined on a specific window, which appears more relevant to the establishment of a roadmap, and also to a specific technology to make intercomparisons, as done in the study presented for CdTe and Si technologies in Figure 10. The LR coefficients are 28.2% for silicon and 25.2 for CdTe, meaning that the two evolutions are not strictly parallel according to this criterion, and that silicon prices are decreasing a bit more rapidly than CdTe with production volume. In the previous study (June 2016) by the same organization, using another extrapolation window, values were 27% and 23.5% respectively. At a given cumulative production, the price of CdTe modules is lower by a factor of 4 to 5 compared to silicon. Strictly reasoning with the comparison of prices at a given production volume this means that CdTe technology is inherently cheaper than silicon technology, with the reason being the simpler production process of thin film technologies with less steps and the module produced at the same time of the cell.

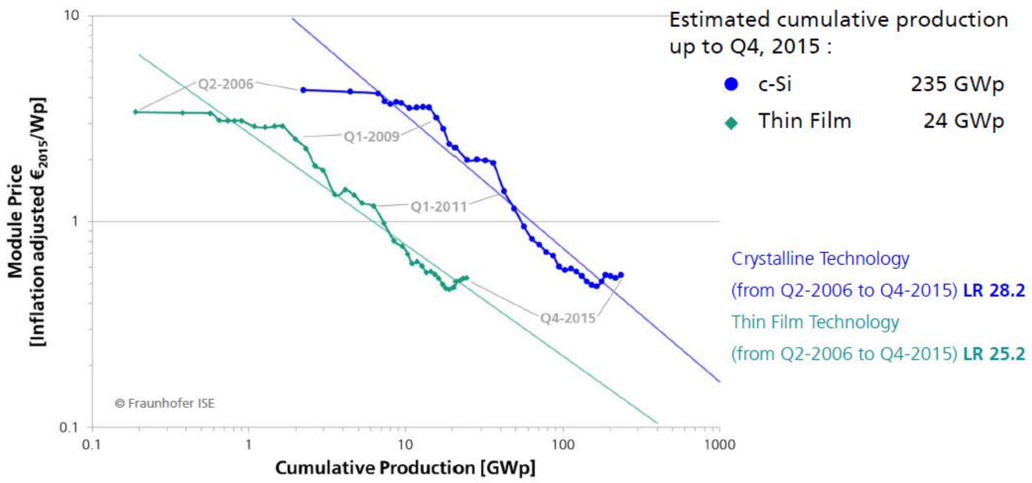



**Figure 10** Learning curves for the prices of PV modules comparing CdTe technology (mainly First Solar) and c-Si technology[15].

Extrapolating the prices to the future, and thus the competitiveness of a given technology among the others, depends very much of the model which is used to analyze basically the same data. This is illustrated in Figure 11 by the studies carried out in the c-Si company TRINA solar[16].

[16] Y. Chen *et al*., "Assessment of module efficiency and manufacturing cost for industrial crystalline silicon and thin film technologies," in *Proceedings of the 6th World Conference on Photovoltaic Energy Conversion*, Kyoto, (Japan), 2014.

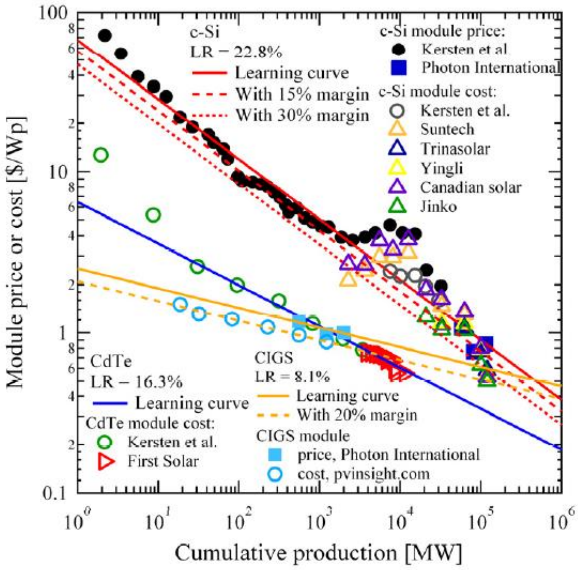



**Figure 11** Learning curves and extrapolation carried out.

In that case, the LR values are 22.8% for c Si, and 16.3% for CdTe. They are slightly different (lower) from those given by the ISE institute, the ratio LR(CdTe)/LR(Si) being reduced from 87% to 71%, making the evolution of the competitiveness of CdTe with the production volume less favorable. From the analysis by Trina Solar, it is expected that in 2020 the cost of Si would be 0.34 $/W and 0.42 $/W for CdTe. However, considering the LR coefficients of ISE the cost in 2020 would lead to a value about 0.3 $/W in both cases. This illustrates the large margin of error which is associated to the predictions up to a few years, using the LR coefficients. Considering this margin of error, a hypothesis that both technologies will remain competitive can be retained.

Another approach to analyze cost evolution (instead of price) and roadmaps, is to represent the evolutions as a function of the years instead of cumulative production. The advantage is to have explicitly the time parameter. This analysis has been performed in Green 2016[13] and is shown in Figure 12.

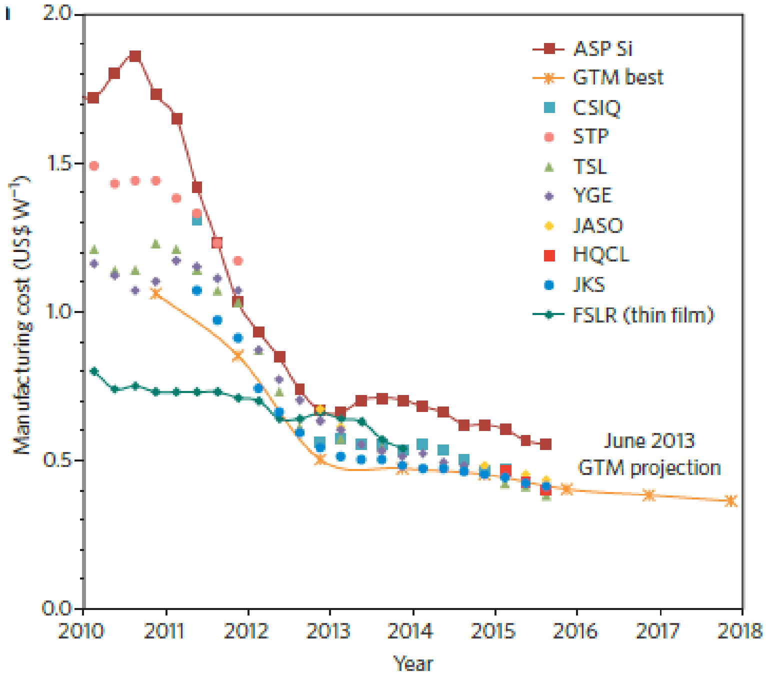



**Figure 12** Evolution of module manufacturing costs presented as a function of the c-Si suppliers and for a thin film manufacturer (First Solar)[13].

It shows a tendency for Si costs to flatten, which is also indicated in the projections by GTM up to 2018 at 0.4 $/W. CdTe costs are equivalent to Si technologies. It has to be pointed out that the cost values for Si are deduced from prices and assume a given margin from 15 to 30%. In fact, this margin is not given by the producers, which introduced a serious bias of comparison since at opposite the cost of CdTe is indicated by the producer (see below).

**Analysis from First Solar's sources**

Considering now the values given by First Solar allows a meaningful comparison. Table 1 recalls the cost roadmap presented in 2013 until 2015 and the current values[17]. Since 2014 no precise cost values are given for commercial reasons, however one can note that the results were better than forecasted.

[17] First Solar Analyst Day 2016, available at:
http://files.shareholder.com/downloads/FSLR/2968270837x0x884412/1548B782-59A0-4544-A452-989E1FA42BFE/FS_AnalystDay_ManufacturingUpdate.pdf
http://files.shareholder.com/downloads/FSLR/1389118248x0x884409/FA8762BE-3405-48FA-95AB-C9ED37E905F6/FS_AnalystDay_FinancialUpdate.pdf

| Cost | | 2013 | 2014 | 2015 |
|---|---|---|---|---|
| Module Cost per Watt (Fleet Average) | Predicted | $0.61 | $0.53-$0.54 | $0.47-$0.49 |
| | Actual | $0.59 ✓ | Exceeded* ✓ | Exceeded* ✓ |
| Module Cost per Watt (Fleet Q4 Avg) | Predicted | $0.58 | $0.52-$0.53 | $0.45-$0.47 |
| | Actual | $0.56 ✓ | Exceeded* ✓ | Exceeded* ✓ |

**Table 1** Cost roadmap for modules of First Solar[17].

These numbers are coherent with the external values given in the previous section. Prospects towards mid-term or long-term are not given. These values made CdTe competitive with respect to the competing silicon technology, even with a much smaller market size. The margin of progress with increasing the production is higher. Note that the potential opportunities for deploying CdTe power plants are significantly increasing from 5.5 GW in 2013 to 14 GW in 2015 to 20 GW in 2016, representing a 400 % increase in 3 years[17].

Thus as compared to silicon technologies, CdTe technology is very competitive in terms of production costs, note that the values are not given in production costs for silicon but in selling prices in Figure 10. This is reflected by the fact First Solar claims to be the only PV company which is in positive financial balance[17].

First Solar's long-term cost roadmap includes reduction in the complete CdTe PV value chain.

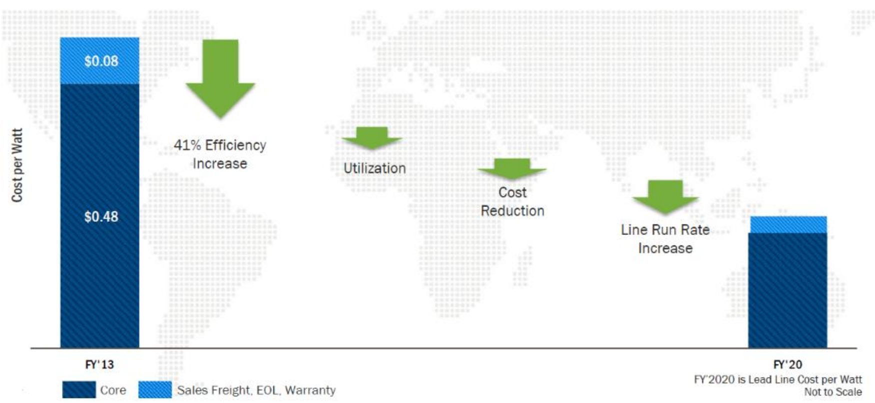



**Figure 13** First Solar's module cost reduction until 2020.

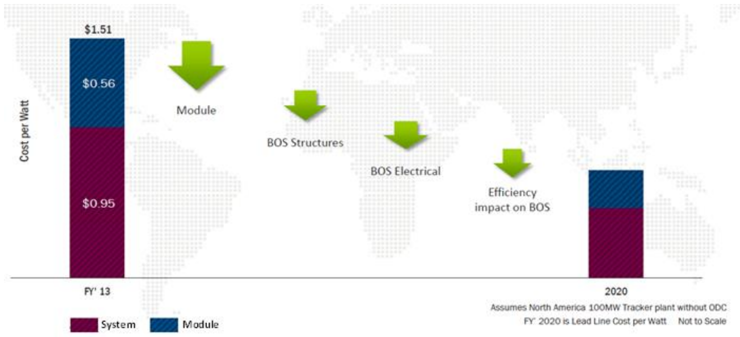



**Figure 14** First Solar's plant cost reduction until 2020.

As it is depicted in Figure 13 and Figure 14 (not to scale), at module level, cost reduction is focused on a 41% efficiency increase (mostly achieved) and improvements in manufacturing operations based on equipment utilization, cost reduction and throughput increase. The indicated value is about 0.25 $/W in 2020, which is significantly lower than the values given from external sources. At plant level, there is an important effort on BoS cost reduction. These opportunities include new architectures for 1500 V, medium voltage DC distribution, tracker cost optimization and optimization on the plant design to reduce construction and installation costs[17].

In some studies on competing thin film technologies the projected cost evolution in longer term is also approaching 0.2 €/W[4] which is closer to the value given by First Solar.

## 2.2.- QUALITY MANAGEMENT AND FIELD PERFORMANCE

This section aims at evaluating performance aspects of First Solar's thin film CdTe PV technology for installation in European regions. In particular reliability issues, field performance as well as grid integration topics will be discussed.

### 2.2.1.- QUALITY MANAGEMENT

The competiveness of PV power plants is defined through its levelized cost of energy (LCoE). Here, the total costs as well as the total amount of energy generated throughout the complete PV module lifetime are taken into account. First Solar is optimizing for maximum energy yield and predictability at extended product lifetimes of up to >25 years. Reliable energy production is assured through product warranties of up to 10 years and performance warranties of more than 80% of the initial power for 25 years.

First Solar maintains an elaborate quality and reliability program comprised of quality control, accelerated indoor testing laboratories, as well as outdoor test facilities in close interaction with failure diagnostics and continued product development. Valuable performance feedback is obtained from a close loop to Power Plant Monitoring. First Solar has reliability laboratories in U.S. and Malaysia and reliability test sites globally including Europe (Figure 15).

#### 2.2.1.1.- Laboratory testing

First Solar's reliability laboratories are ISO 17025 accredited with automated equipment and data collection as well as an extensive personnel training program[18]. Table 2 gives some metrics on the extensive reliability testing program currently in place at First Solar's manufacturing facilities in the USA and Malaysia, as well as at test sites around the world.

| | Active Capacity |
|---|---|
| Modules tested per year (% of total module production per year) | >80.000 modules (>0.4 %) |
| Modules currently in test | >4.000 modules |
| MW tested per year | >8 MW |
| Reliability lab space | 6000 $m^2$ |

**Table 2** First Solar metrics on PV module Quality and Reliability infrastructure in 2015.

First Solar's reliability laboratory supports product quality control in high volume manufacturing (production monitoring), new product and process development (technology development), product reliability (product and process qualification and certification, assistance in the preparation of technical notes and product data sheets), and warranty (accrual predictions and field performance validation).

An in-house test laboratory carries out accelerated lifetime testing of products and packages. The reliability laboratory is capable of performing all demanded tests by the IEC 61646 and IEC 61730-1&-2 and often beyond these standards.

***Module power characterization***

Power characterization of PV modules at Standard Test Conditions is performed with a Class AAA solar simulator according to IEC 60904-9 ed.2. Further performance characterization at varying temperatures and irradiance conditions is possible. Quality assurance includes module thickness measurements, to characterize PV module thickness and relative shape, automated visual inspection, to detect any visual defects in the PV module, and near-IR measurements, to detect any defects in the module which are visible as a result of electroluminescence.

***Accelerated climate testing (e.g. temperature, humidity, UV irradiation, wind, hail)***

This includes tests in climatic chambers to access module behavior with respect to temperature and humidity (59 chambers). UV chambers are used to accelerate UV exposure in order to

[18] P. Buehler; "First Solar Quality & Reliability Strategy", *in IEEE PVSC*, New Orleans, 2015.

evaluate materials and adhesive bonds susceptible to UV degradation. Light-soaking is performed to accelerate light induced degradation and for module stabilization. In total 136 chambers are under operation.

Static and dynamic load equipment is utilized to simulate wind, snow and ice loads at varying temperatures and rates and ensure module integrity under those loads. In a hail impact test, PV module capability of withstanding the impact of hail is verified.

***Safety testing (e.g. fire, breakage, high voltage)***

Further safety tests are carried out. In reverse current overload (RCOL) the risk of fire under reverse current fault conditions is determined. The module breakage test ensures that cutting or piercing injuries are minimized when a PV module is broken. Hot spot testing determines the ability of a PV module to withstand heating effects caused by soiling or shading, while the impulse voltage test verifies the capability of the solid insulation of the PV module to withstand over-voltages caused by a lightning strike. With a wet and dry HiPot measurement facility insulation of the PV module under wet operating conditions is evaluated and verified that moisture does not enter the active parts.

***Long-term stress exposure***

First Solar has recently undertaken long-term parallel testing in recognition of the need to extend test durations to better differentiate PV modules in long-term field performance[19]. For example, in the Thresher Test, the conventional IEC test environmental stress exposure durations are multiplied by a factor of two to four in order to identify those modules with truly differentiated long-term reliability and performance. First Solar is the first thin-film PV manufacturer to pass the extended accelerated life cycle testing protocols of the Thresher Test and Long Term Sequential Test[20], and one of only four modules in the world to pass the Atlas 25+ durability test. First Solar PV modules are also certified for reliable performance in extreme desert and coastal environments (IEC 61701 Salt Mist Corrosion, IEC 60068-2-68 Dust and Sand Resistance) and have a UL 1703 and ULC 1703 Listed Class B Fire Rating (Class A Spread of Flame). First Solar is also the first PV company to obtain the new VDE Quality Tested (QT) Certification for PV power plants (module and balance of system)[21].

#### 2.2.1.2.- Outdoor reliability testing

A global infrastructure of outdoor proving test sites provides performance and reliability data from major climate regions ranging from hot arid, hot humid to temperate. For this purpose First Solar operates outdoor test sites with 320 kW to 350 kW at Arizona (US), Ohio (US), Malaysia and 36 kW at Chile, India and Philippines (Figure 15). In Europe, field reliability monitoring sites are located in Germany and Spain, and First Solar has deployed over 4GW in projects ranging

[19] N. Strevel *et al.*, " Improvements in CdTe module reliability and long-term degradation through advances in construction and device innovation", *Photovoltaics International*, vol. 22, pp. 1-8, December 2013.
[20] P. Sinha *et al.*, "Life cycle materials and water management for CdTe photovoltaics", *Solar Energy Materials & Solar Cells*, vol.119, pp. 271-275, 2013.
[21] VDE, Fraunhofer ISE award First Solar first quality tested certification. PV Magazine 22 October 2014, available at : http://www.pv-magazine.com/news/details/beitrag/vde--fraunhofer-ise-award-first-solar-first-quality-tested-certification_100016892

in size from a few tens of kW to over 30 MW each. Data is acquired with the aim of competitive benchmarking, evaluation of technology readiness, optimizing performance and reliability modeling and improving bankability. Examples of the largest projects in Europe using First Solar modules are:

- Crucey, 60 MW, France, Year 2012; http://www.edf-energies-nouvelles.com/wp-contenu/uploads/2012/09/dp_centralepv_crucey_eng.pdf
- Gabardan, 67 MW, France, Year 2011;

  http://www.pvtech.org/news/edf_energies_nouvelles_commissions_67.2mw_plant_in_france_utilizing_first_s
- Landmead, 46 MW, UK, Year 2014;

  http://www.pv-magazine.com/news/details/beitrag/belectric-and-first-solar-connect-uks-largest-solar-farm_100017577/#axzz4SlWQqqXd
- Lieberose, 53 MW, Germany, Year 2009; http://investor.firstsolar.com/releasedetail.cfm?releaseid=571585
- Massangis, 56 MW, France, Year 2012;

  http://www.edf-energies-nouvelles.com/en/press-release/edf-energies-nouvelles-commissions-a-56-mwp-solar-power-plant-in-massangis-france/
- Templin, 128 MW, Germany, Year 2012; http://www.belectric.com/fileadmin/MASTER/pdf/press_releases/pm_BEL_2013_0422_Inbetriebnahme_Templin_EN.pdf
- Waldpolenz, 52 MW, Germany, Year 2008, https://www.revolvy.com/main/index.php?s=Waldpolenz%20Solar%20Park&item_type=topic

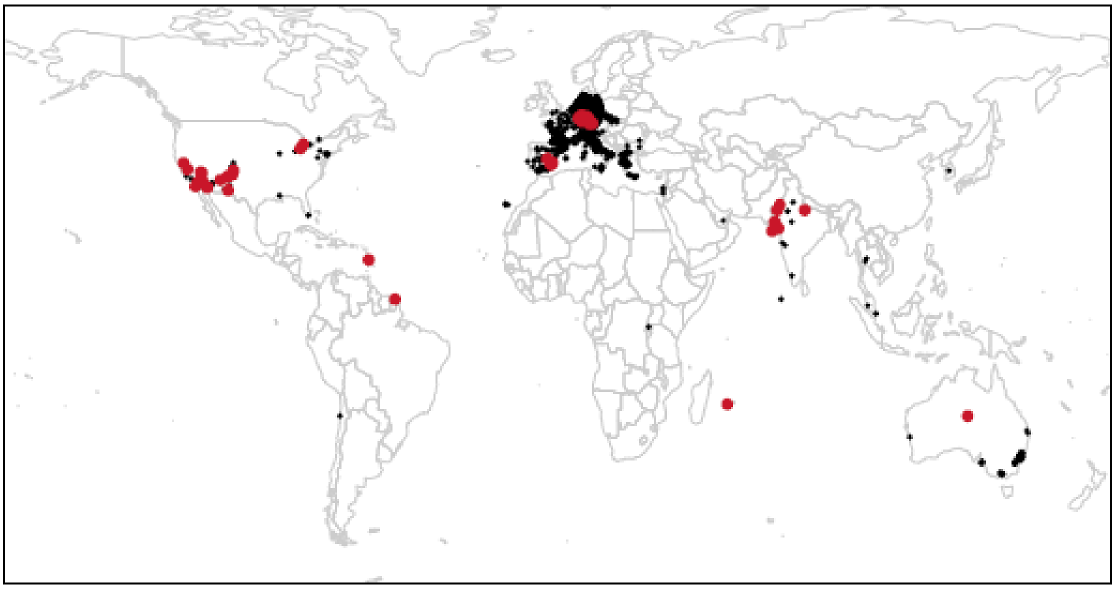


**Figure 15** Location of First Solar power plants (black dot) and field reliability monitored sites (red dot)[19].

First Solar's outdoor test facilities are embedded in a close quality and reliability cycle between technology development, qualification, verification and validation. Critical performance parameters and operation conditions for specific module designs are investigated in depth in order to better understand product behavior and yield prediction. For example the impact of Cu diffusion has been thoroughly investigated and engineered in recent years[19]. Specifications and guidelines to prevent e.g. soiling and potential induced degradation are available[22]. Furthermore, characteristic features of First Solar modules with a particular impact on performance, like thermal coefficients of efficiency, spectral response, have been analyzed and quantified with high precision[23]. Finally, performance monitoring at GW range system level supports the creation and validation of energy models over the complete lifetime of First Solar modules[24].

#### 2.2.1.3.- Failure diagnostics

First Solar employs a Failure Mode and Effects Analysis (FMEA) as a main driver for product innovation and development. In order to go beyond standard testing and understand the physics of failure, high-level characterization and diagnostics laboratories are operated in Perrysburg, Ohio, Santa Clara, California, and Mesa, Arizona in the US, and in Kulim, Malaysia.

The laboratory for materials characterization and diagnostics is equipped with state-of-the-art instrumentation for semiconductor device characterization and microstructure analytics, including various sample preparation techniques as well as high-resolution imaging (e.g. electron microscopy, focused ion beam techniques) and analytics (e.g. TOF secondary ion mass spectrometry, ICP mass spectrometry). A systematic and routine material data acquisition is performed in order to provide a quantitative backbone for product quality and development.

The laboratory for product development is performing advanced research and development at test structures, modules and module components. Specific issues in device performance and reliability are addressed through extended test sequences and non-standard test setups.

The module package is constantly improved for reliability. The S3 Black module design introduced a new high-performance olefinic encapsulant and an improved butyl-based edge sealant material[20]. The water vapor transmission rate (WVTR) of the encapsulant is several times lower compared to most conventional EVA-based thermosetting encapsulants and therefore acts as a secondary barrier to water ingress. The volume resistivity of S3 encapsulant ($10^{15}$ Ω·cm) is also two orders of magnitude higher. Another feature is a high bond strength to glass even after 2,000 h damp heat (85 °C, 85% R.H), 200 thermal cycles (-40 °C, - 85 °C) and hot water immersion. The current S4 technology is based on these improvements.

[22] G. Hasmann, "Technology Assessment Report", Fichtner, 2015.
[23] D. Weiss, "New Photovoltaic Materials and Devices from the Perspective of a Utility PV Company," EE1.4.01, MRS Spring Meeting, Phoenix, 2016.
[24] K. Passow *et al.*, "Accuracy of Energy Assessments in Utility Scale PV Power Plant using PlantPredict," in *IEEE PVSC*, New Orleans, 2015.

## 2.2.2.- FIELD PERFORMANCE

### 2.2.2.1.- Overall module and system performance

The extensive product reliability testing strategy of First Solar, ranging from laboratory to outdoor performance testing, has led to fundamental technological improvements over the last years. Long-term stability of energy yield of First Solar's thin-film CdTe PV modules has been achieved from continuous advances in CdTe research and development. Due to the strong system integration activities of First Solar, a broad list of topics is covered which range from module field performance over utility-scale PV power plant monitoring and performance to climate-specific soiling issues.

***PV module field performance***

In a long-term experiment with First Solar (formerly Solar Cells Inc.) 1995-vintage thin-film CdTe PV modules, after almost two decades of monitoring, the US National Renewable Energy Laboratory (NREL) confirms the excellent reliability of First Solar's module technology, with no module failures in system operation[25]. Over 17 years (1995-2012) a -0.53 %/year degradation rate in the temperate climate of Colorado (US) was observed.

First Solar has characterized module performance in particular in hot climates, addressing the challenges to PV power plants operated under elevated temperatures. The following points are listed as particular answers of First Solar CdTe technology to these challenges:

- CdTe's lower magnitude temperature coefficient provides improved energy yield in hot climates, where modules are operated mostly above 25°C cell temperature.
- Expected initial field-stabilized efficiency values for hot climates are known and taken into account in the module nameplate.
- Energy yield prediction accounts for first year degradation and long-term degradation. Recommended values have previously been -0.5%/year for moderate climates and -0.7%/year for hot climates, though a recent addition of a ZnTe-based back contact has resulted in current degradation guidance of –0.5 %/year in all climates (see below).
- Root cause and physical mechanisms of long-term degradation have been extensively investigated and are understood in order to provide reliable prediction, mitigation and accelerated laboratory testing.

Results of extended reliability tests were presented upon introduction of First Solar's cell structure in 2013 with improved back-contact design that better manages the fundamental power output degradation mechanism inherent to CdTe PV devices[19]. Accelerated laboratory testing methods, field testing and associated analyses have been performed at many sites around the globe. Since then, First Solar's Series 3 'Black' PV module series has been continuously developed towards the current First Solar Series 4 PV module.

[25] N. Strevel *et al.*, "Performance characterization and superior energy yield of First Solar PV power plants in high-temperature conditions", *Photovoltaics Internationa*l, vol.17, pp.148–154, 2012.

Advances in solar cell performance coupled with upgraded module materials and design have been thoroughly investigated with respect to particular degradation effects[22]. Cu diffusion related power stabilization and degradation as well as potential induced degradation (PID) have been studied with respect to impact and measures for mitigation. The total annual degradation for modules manufactured after 2000 is below 0.5 %/year.

A modest amount of Cu increases the CdTe-based cell performance, while excessive amounts of Cu degrade the device quality and decrease performance. The diffusion of Cu and the formation of copper sulphide (CuS) together with an overlap of processing parameters results in conditions in the module that accelerate the degradation mechanism. According to First Solar, its modules contain a very moderate amount of Cu used for back-contact layer formation and CdTe absorber-layer doping.

PID is linked to the leakage current passed from the photovoltaic active layer, such as silicon for c-Si based solar cells, through the encapsulant and glass to the module frame. PID is also known as high voltage stress (HVS). This is an up to 80% loss of PV system power caused by leakage current at high voltages. Since First Solar modules are frameless, the only path possible for the PID responsible leakage current is through clamps or back rails. The risk of potential leakage currents has been minimized with the introduction of a minimum volume resistivity requirement for the inlay material of First Solar approved mounting clips for Series 4 and Series 4V2 modules.

Performance and reliability have been evaluated for typical outdoor operation and stress conditions ranging from temperature behavior, PID, shading effects and spectral response to angle of incidence. Figure 16 shows the improved spectral response at low wavelength for Series 4V2 PV modules in comparison to previous generations and Si PV modules. The improved spectral response at wavelengths below 500 nm is one major reason for the outdoor performance achieved with latest CdTe technology generations (see section 2.2.2.2.-).

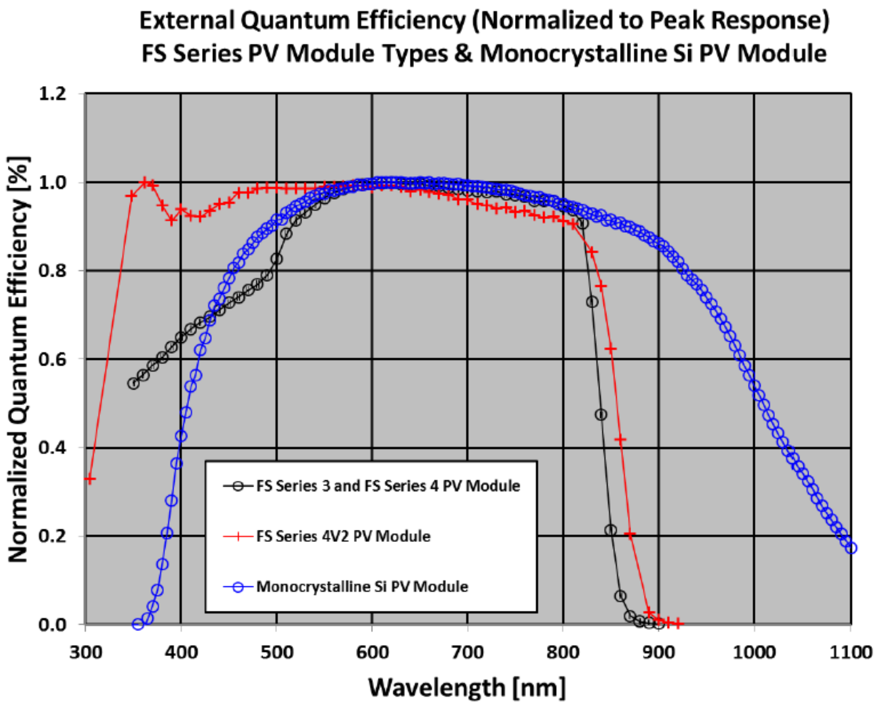



**Figure 16** Normalized external quantum efficiency of First Solar FS Series 3, FS Series 4 and FS Series 4V2 CdTe PV module types compared with that of a single-crystalline Si PV module[23]. The specific properties of CdTe outdoor performance can be directly derived from its characteristic spectral response at short wavelengths (< 500 nm).

### *Utility-scale PV power plant performance*

Utility-scale PV power plants have a significant impact on the electricity management in European grids with an increasing share of PV energy generation[26,27], but little is known on their specific performance, the time-resolved measured or calculated power output. The bankability of a PV power plant is largely determined through a calculation of the long-term average annual energy yield. One common strategy for generating long term predictions uses satellite meteorological data and estimated loss assumptions along with a common PV energy simulation tool, such as PVsyst[28] .

Panchula *et al.*[29] compared the measured output performance of the Sarnia 20 $MW_{AC}$ power plant in Ontario (Canada) after one year of continuous operation to its predicted output. Based on the first year's data, the power plant was shown to be operating 2.1% above the long-term prediction, well within the expected error-bars of modeling uncertainty. Thus, systematic deviation in predictive modeling could be excluded. At the same time, the precision of underlying loss assumptions for the first year operation could be verified.

A comparative and predictive energy yield assessment comparing performance of different module technologies at the utility-scale level was performed in 2015 for hypothetical locations

[26] Google Earth 2016 First Solar Europe Greater Than 3MWdc, data provided by First Solar.
[27] Google Earth 2016 First Solar Europe Less Than 3MWdc, data provided by First Solar.
[28] http://www.pvsyst.com/en/
[29] A. F. Panchula *et al.*, "First year performance of a 20MWac PV power plant," *in 37th IEEE PVSC*, Seattle, WA, 2011.

and power plants in England[30,31]. The studies aim at a comparative evaluation of different module technologies. Based on a set of system, irradiation/weather as well as degradation assumptions, three multicrystalline Si based systems and one First Solar based system were modelled. Depending on detailed degradation rate assumptions, a close distribution of the cumulative energy production over 20 years, of 37,238,000 ± 5% kWh[31] has been obtained.

A fundamental methodological investigation on the accuracy of plant power prediction approaches was performed by First Solar[32]. First Solar's own performance prediction software (PlantPredict) was compared to PVsyst, showing agreement from 51 simulation runs on average at 0.13% ± 0.52%. Measured performance of 20 utility scale systems representing nearly 1 GW of First Solar modules was also compared to predicted performance using First Solar's modeling guidance. On average, PlantPredict underpredicted energy on average by 0.41% ± 2.01%.

The predicted energy ratio (PER) of a particular PV module or system is the lifetime ratio of actual energy produced to the energy predicted. Figure 17 shows the average PER by commissioning year for several systems of a total power of 270 MW (including >130 MW deployed in hot climates) of installed PV systems using First Solar's CdTe modules. The PER substantiates First Solar's field performance record and validates First Solar's accuracy in predicting field performance. Current degradation guidance of –0.5 %/year, in all climates, is First Solar's recommendation for long-term performance PV systems modeling[19]. This degradation guidance has been determined based on accelerated laboratory testing[33] under elevated temperature, high voltage bias and irradiation with particular regard to ZnTe-based back contact performance assessment.

[30] Sgurr Energy, "Comparative Energy Yield Assessment", 2015.
[31] OST Energy, "Comparative Yield Analysis", 2015.
[32] K. Passow *et al*., "Accuracy of Energy Assessments in Utility Scale PV Power Plant using PlantPredict," *in IEEE PVSC*, New Orleans, 2015.
[33] D. S. Albin, "Accelerated stress testing and diagnostic analysis of degradation in CdTe solar cells", in *Proc. SPIE*, vol. 7048, 1, 2008.

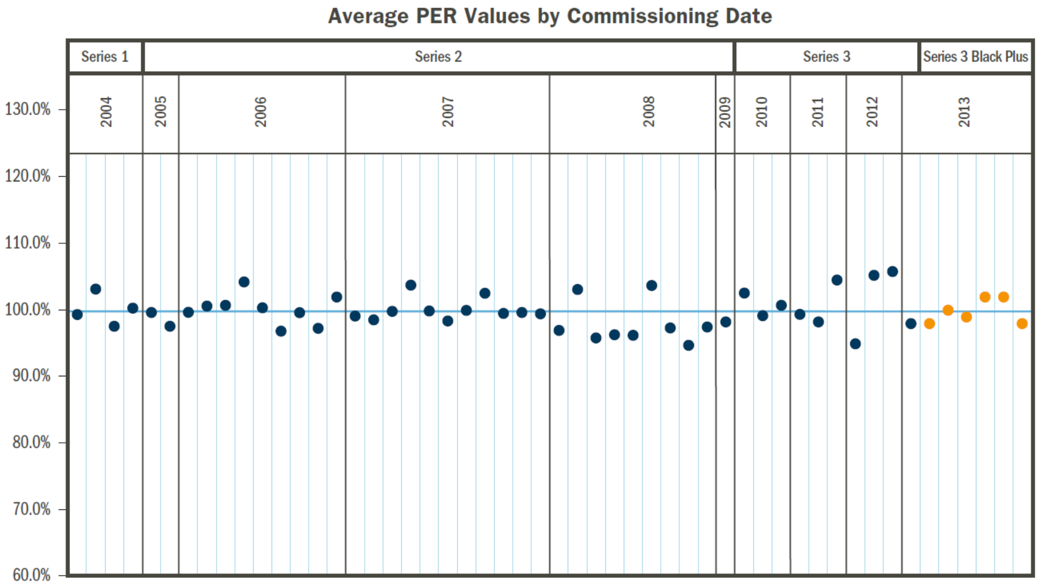



**Figure 17** Average Predicted Energy Ratio (PER) by commissioning year for 270 MW of thin-film CdTe PV systems using First Solar modules: >270 MW monitored installations base, including >130 MW of hot-climate deployments[34]. Orange dots highlight the performance of the production series (S3 black plus) with included ZnTe back contact.

### 2.2.2.2.- Performance under specific conditions

The power of a PV module is rated with respect to standard test conditions (STC) which are defined by a 1000 W/m² light illumination corresponding to AM1.5 spectral distribution and an operating cell temperature of 25 °C. These conditions allow a direct comparison among different PV technologies. However, in real operating conditions, the illumination level, spectral distribution, and module temperature do not always match those values. The temperature of the module can reach 50 ºC to 80 °C, far from the 25 °C STC conditions. The illumination level also varies from low levels to upper levels (0 to about 1300 W/m² depending on the location and specific atmospheric characteristics). Finally, the spectral distribution can also differ from AM1.5 STC conditions depending on the contents of the atmosphere, which can result in varying amounts of irradiance at certain wavelengths; depending on the module's spectral response, this can change the module's performance by a significant amount.

To better account for the differences between standard test conditions and real operating conditions, a new standard has been settled, IEC-61853 *"Photovoltaic module (PV) performance testing and energy rating"*, with four different parts. Specifically, Part 1 takes care of matrix irradiance/temperature and Part 2 is dedicated to spectral responsivity, incidence angle and operating temperature measurements[35]. The information obtained out of the application of those standards characterizes the "in the field" module performance, and new parameters are defined for that. The concept of Nominal Module Operating Temperature (NMOT) represents the temperature of the module in a reference environment of 800 W/m² with the light spectrum being the same as for STC, and simulated wind of 1 m/s speed with air at

[34] L. Ngan *et al.*, "Performance characterization of Cadmium Telluride modules validated by utility-scale and test systems", in *IEEE PVSC*, 2014.
[35] IEC-61853-2, "Photovoltaic (PV) module performance testing and energy rating-Part 2: Spectral responsivity, incidence angle and operating temperature measurements," Ed. 1, September 2016

20°C added. This NMOT value, which must be obtained for every model of module, is representative of conditions during field operation.

Concerning the spectral distribution, that depends on the different air mass levels, on the angle of incidence of the solar radiation and the water vapor present in the atmosphere (among other causes). The spectrum used as reference appears on the IEC-60904-3 standard, and however, depending on the geographical location and climatology, this spectrum can vary. For example, areas with hot, humid climates have high levels of water vapor, creating a large positive spectral adjustment for CdTe modules compared to a reference broadband device.

Finally, the specific energy yield of a PV module for determined atmospheric conditions, expressed in kWh/kWp, corresponds to the ratio between the produced electric energy (kWh) and the STC-rated power of the module (kWp). This is a parameter representative of "in the field performance" and can be used for comparison among various technologies for a given geographical site.

All those facts support the well-known point of the importance of considering spectral shifts and temperature influence when deciding the use of a given module technology in a specific location, rather than purely the module nameplate power.

***Temperature effect***

The effect the temperature has on the performance of a PV module is basically related to the band gap of the semiconductor material used as absorber in the solar cell and has also some influence from the interconnecting and encapsulating processes on the module technology. This effect increases as the band gap of the semiconductor decreases. The band gap of CdTe is about 1.45 eV while that of silicon is 1.12 eV[36]. Figure 18 compares the temperature coefficient of CdTe modules to that of silicon as a function of temperature.

[36] M.A. Green, "General Temperature Dependence of Solar cell performance and implications for device modelling," *Progress in Photovoltaics: Research and Applications*, vol. 11, pp. 333-340, 2003.

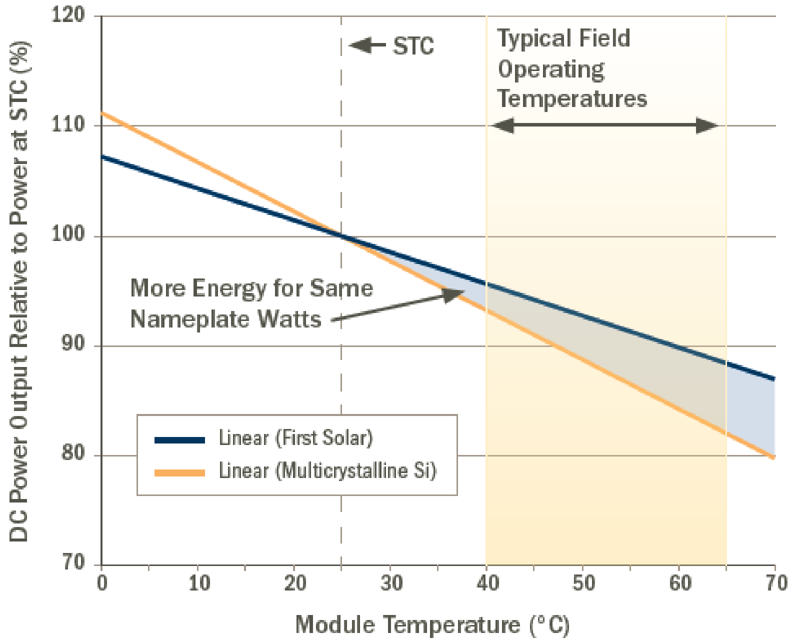



**Figure 18** Comparison between the temperature dependence of CdTe modules with respect to multicrystalline silicon. First Solar's Series 4 and 4A temperature behavior (blue line) and standard multi c-Si modules (orange line) versus module output power (First Solar Series 4 data sheet) modules[37].

The temperature coefficients are given in the specification sheets of every PV module. Values for various models of CdTe modules provided by First Solar are shown in Table 3.

| First Solar | | | |
|---|---|---|---|
| | **FS (-492/-495/-4100/-4102)A** | **FS(-4102/-4105/-4107/-4110/-4112)-2/A-2** | **FS(-4107/-4110/-4112/-4115/-4117/-4120)-3/A-3** |
| **Maximum Power ($P_{MPP}$)** | 92.5/95/97.5/100/102.5W | 102.5/105/107.5/110/112.5 W | 107.5/110/112.5/115/117.5/120 W |
| **Tolerance Power** | +/-5% | +/-5% | +/-5% |
| **Efficiency** | 12.8/ 13.2/ 13.5/ 13.9/ 14.2% | 14.2/ 14.6/ 14.9/ 15.3/ 15.6% | 14.9/ 15.3/ 15.6/ 16.0/ 16.3/16.7% |
| **Temperature Coefficient of ($P_{MPP}$) (average)** | -0.29%/°C | -0.34%/°C | -0.28%/°C |
| **Temperature Coefficient of Voc** | -0.28%/°C | -0.29%/°C | -0.28%/°C |
| **Temperature Coefficient of Isc** | +0.04%/°C | +0.04%/°C | +0.04%/°C |

**Table 3** Temperature coefficients of CdTe modules from First Solar data sheets[38].

The temperature coefficients of $P_{MPP}$ of -0.29 %/°C for the FS 4, -0.34 %/°C for the FS 4V2 , and -0.28 %/°C for the FS 4V3 Series modules are lower than the temperature coefficient of crystalline Si wafer-based modules (approximately -0.43 %/°C) and CIGS (approximately -0.4 %/°C).

As a consequence, it appears that, in typical module operating field temperatures, the loss of power rating of the modules due to temperature increase is lower in CdTe modules as compared to c-Silicon modules.

[37] Fichtner "First Solar Technology Assessment Report" 2015.
[38] First Solar Module Data Sheet.

***Spectral response effect in humid climates***

The spectral response of PV technologies depends also on absorbing semiconductor material and on other components of the PV module manufacturing technology itself. The spectral effects are recalled in Figure 19 for both CdTe and standard c-Si modules[39]. In the image, the spectral distribution of light in two representative cases of STC conditions (AM1.5 spectrum, light blue) and light spectral distribution with high precipitable water content (dark blue). It is shown that the difference mostly appears on the absorption bands of water, around 950 nm and 1150 nm, with a lower irradiance in these domains when the atmospheric water vapor content increases. These spectral differences between real operating conditions on high humidity environments and standard test conditions introduce differences in the energy yield of the modules as compared to those predicted by the STC spectrum.

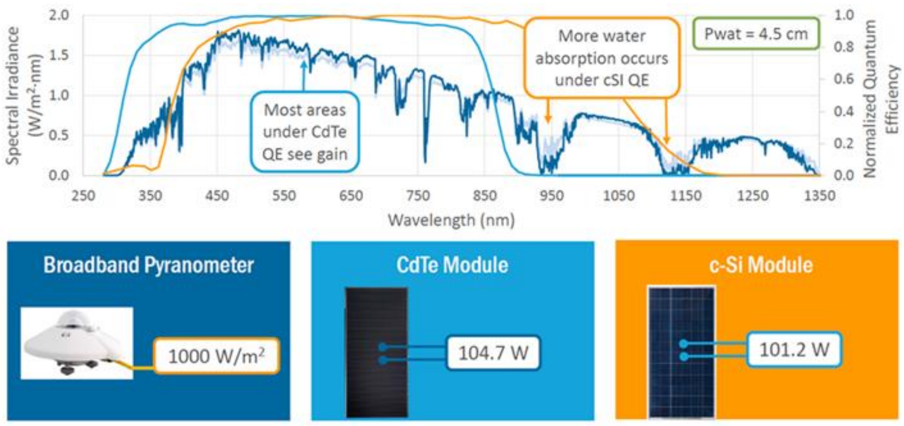



**Figure 19** Effect of spectral changes related to the humidity level on the power output of CdTe modules compared to Si modules.

Taking into account the spectral responses of CdTe and Si, it appears that water absorption does not affect CdTe response while affecting that of Si, especially around 950 nm where its quantum efficiency is high. The second absorption band, at around 1150 nm, also affects the Si response but more weakly since it is situated in the wavelength region where the quantum efficiencies of Si are lower. However, in the case of high quality silicon solar cells, since their quantum efficiencies are higher in this domain, the impact of spectral modification due to humidity in the final performance of the modules would be also higher.

The consequence of this spectral matching is that CdTe modules have lower losses due to water vapor modification of solar spectrum than c-Si modules as shown in Figure 19 (bottom). Assuming 1000 W/m$^2$ incident irradiance under reference spectrum (AM1.5), two CdTe and Si modules equally rated in efficiency under STC conditions will deliver the same output power, for instance 100 W. When moving to humid climate, due to the spectral response difference, this will result in an increase of the output power of both technologies, however due to the increased losses for silicon in the water absorption band, which do not affect the CdTe response, the relative increase is higher for CdTe (104.7 W versus 101.2 W) for the same global energy

[39] N. Strevel, “Technology Roadmap” 2016.

irradiance.

As for the rest of parameters influencing the electricity generation out of PV technology, this case, specific of certain geographical areas, must be taken into account and important efforts are carried out to include that factor in the simulation tools and energy production models[40,41]. Besides, extensive external studies have been carried out also especially for Europe at CIEMAT and the University of Jaén[42].

***Global effect in Hot and Humid Climates***

In climates that are both hot and humid, temperature effects and spectral effects are added meaning that the benefit for CdTe modules over silicon modules is evaluated by First Solar as up to 8% depending on the location. The announced progress of the efficiency of CdTe modules as compared to Si modules increases the benefit of CdTe modules with respect to Si modules in hot and humid climates up to 11%[43]. However, it can be noted that an improvement of the STC efficiency by reducing the band gap can reduce the beneficial effect of increasing the temperature.

Figure 20 gives an overview of the geographical and atmospheric influences based on results from PVSyst simulation of different locations using CdTe and a reference c-Si technology[44]. As it can be derived from this figure, the beneficial effect for CdTe is the strongest performance in hot and humid climates (up to 9.1% in India).

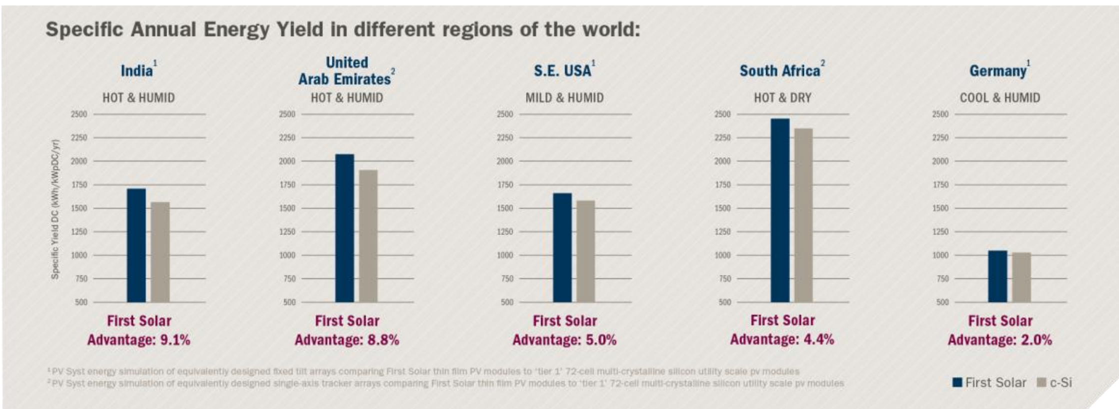



**Figure 20** Energy yield of CdTe modules as a function of the location and local climate in comparison with Si multicrystalline modules.

Figure 21 shows a map of the estimated energy yield advantage presented by First Solar[43] technology depending on geographical and climatic aspects. The highest advantage is situated

[40] L. Nelson *et al.*, "Changes in cadmium telluride photovoltaic system performance due to spectrum," *IEEE Journal of Photovoltaics*, vol. 3, no. 1, pp. 488-493, 2013.
[41] M. Lee *et al.*, "Understanding next generation of cadmium telluride photovoltaic performance due to spectrum," in *IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 14-19 June 2015.
[42] M. Alonso-Abella *et al.*, "Analysis of spectral effects on the energy yield of different PV (photovoltaic) technologies: The case of four specific sites," *Energy*, vol. 67, pp. 435-443, 2014.
[43] First Solar "Technology Roadmap" 2016.
[44] Raffi Garabedian, First Solar's Analyst Day Technology Update 2014.

in hot and humid climate zones in agreement with the previous analyses, reaching up to 13% in particular in India, South America, China and central Africa. We can note that this advantage and its evolution with time is also a consequence of the increase in STC measured module efficiency as a function of technology improvement, while the temperature and spectral effects benefit are remaining more or less constant[44].

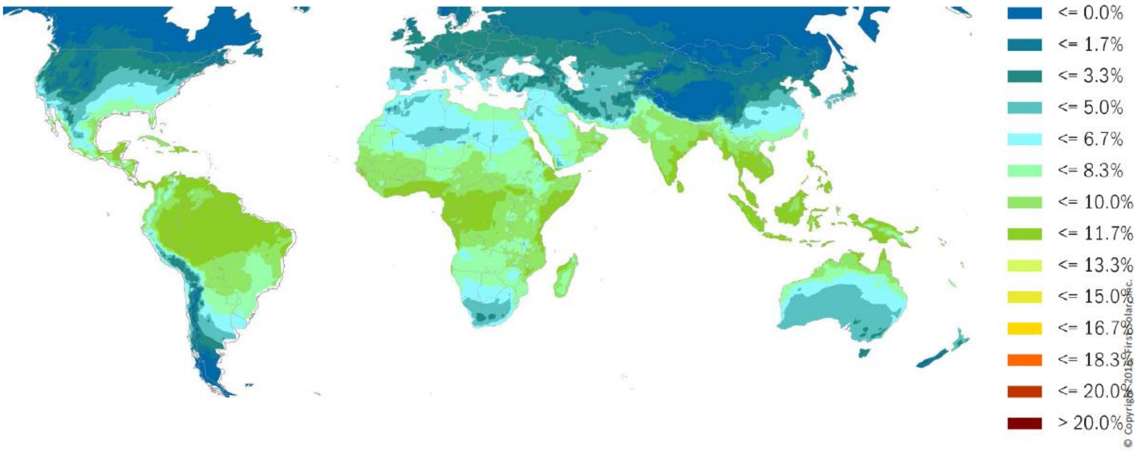



**Figure 21** Effect of location on the comparison between the energy yield of CdTe First Solar Modules and multicrystalline Si modules.

Concerning climatic influence on performance of PV technologies extensive studies have been carried out also especially for Europe at CIEMAT and at the University of Jaén[42] which allows an external benchmarking. The study by Alonso-Abella *et al*.[42] deals with the effect of local climates, on the energy yield of various PV technologies. Three locations in Europe (Jaén, Madrid, Stuttgart) and one in Africa have been studied. Monthly and yearly productions are compared from experimental measurements and simulated ones, by means of the spectral factor (SF). Eight technologies are considered including cadmium telluride. The results confirm the strong effect of local climates, including spectral issues, on the energy yield of solar modules; nevertheless, their conclusion is that specific spectral gains were not so relevant on yearly time scales. Although large variations are seen seasonally, particularly for a-Si and CdTe technologies, the particular locations studied have climates where these effects tend to average out on an annual basis.

Figure 22 (top) shows calculations carried out on a yearly basis for the different technologies at the four above-mentioned locations. It can be observed that a-Si and CdTe have a positive spectral shift factor (i.e. greater than one) in three of the four locations, unlike the other considered technologies. a-Si shows more extreme variation than CdTe, but note that the efficiency of a-Si is also much lower. Note that the simulations and real measurements experiments are still different on the absolute values (Figure 22, bottom) for thin film technologies (experimental values are lower than predicted), while match the results on c-Si based ones. These are results of 2013 and simulation tools usually had been optimized for the dominant technologies (c-Si at those days).

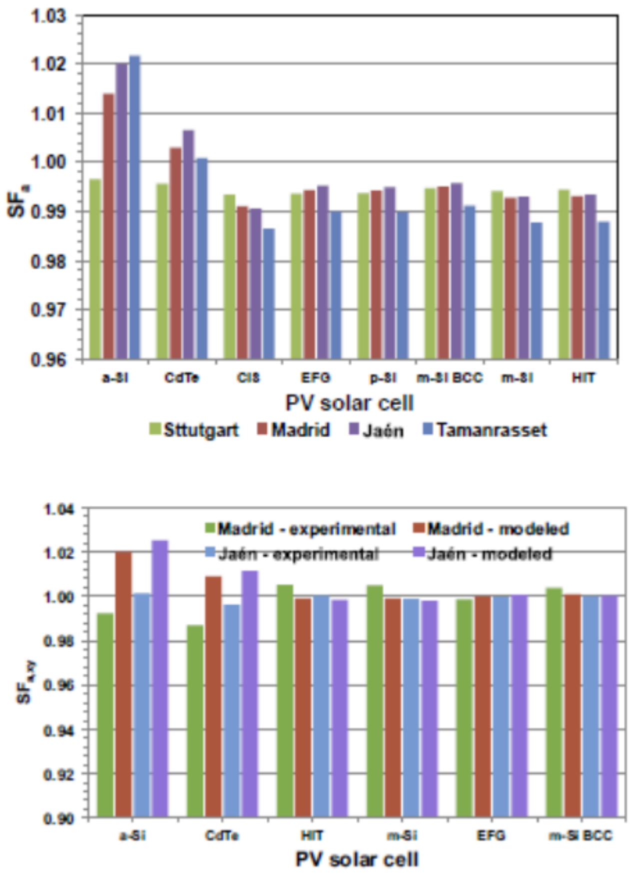



**Figure 22** Top: Modeled figures of the spectral factor for different technologies and locations. Bottom: Experimental and modeled figures of the spectral factor for different technologies and two locations in Spain[42].

In the following figure, the modelled spectral factor for the different technologies in Stuttgart is shown. As can be appreciated from this figure, a-Si technology shows the most pronounced variation, increasing from a value of 0.840 during December to 1.040 during June, followed by CdTe technology.

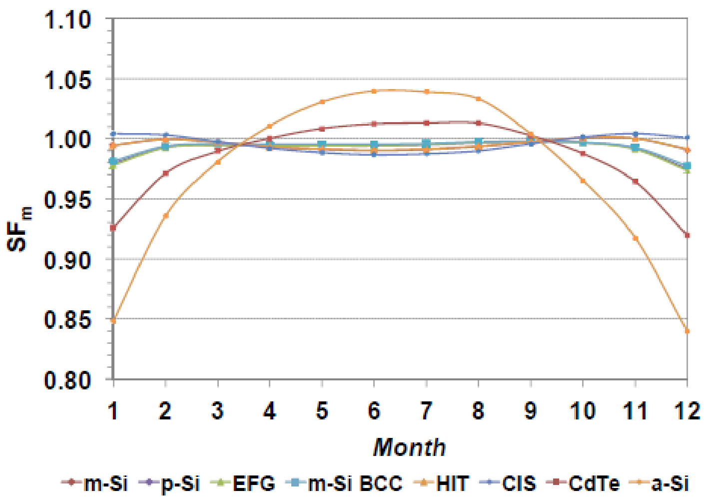



**Figure 23** Modelled data of the spectral factor for the different technologies in Stuttgart[42].

Another in-depth study concerning influence of solar spectral irradiance has been published by D. Dirnberger *et al*. from the ISE Fraunhofer Institute in Germany, based on measurements carried out in Freiburg from June 2010 until December 2013. The spectral irradiance was used to calculate the spectral shift factor for several different technologies, including CdTe[45]. As noted by the authors, this location is close to that of Stuttgart allowing comparison with the result of Alonso-Abella *et al*. The results of monthly spectral impact measurements are shown in Figure 24. As in the previous work, seasonal variations are apparent, with larger positive benefits in the summer for a-Si and CdTe, and smaller magnitude adjustments for c-Si with a minimum during the summer.

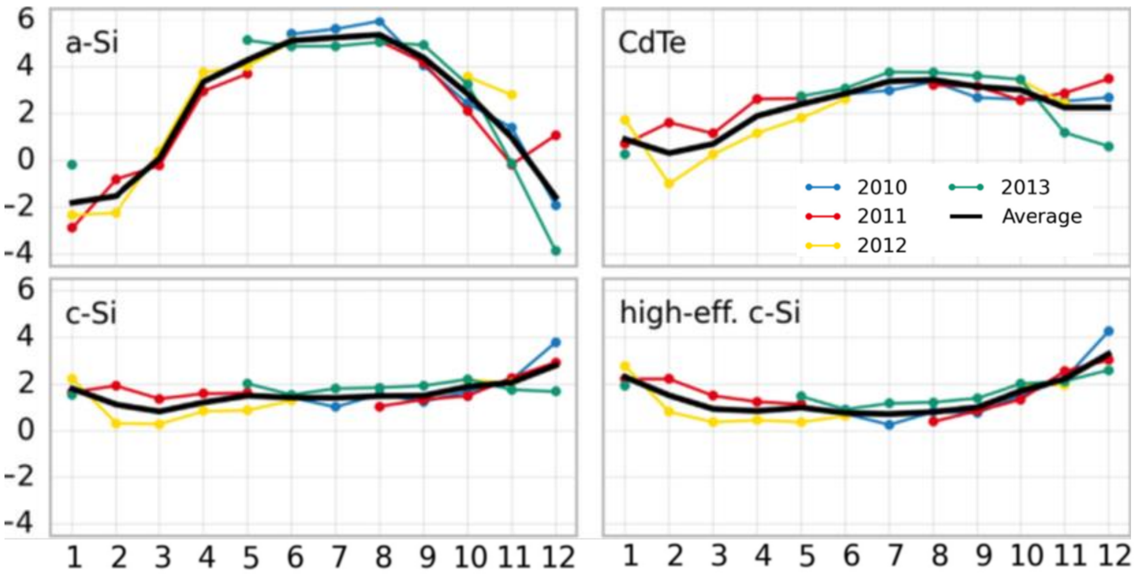



**Figure 24** Monthly Spectral impact of PV technologies over 3 years measurements made in Freiburg (Germany)[45].

Although the results presented by both groups agree well qualitatively, Alonso-Abella *et al.* report spectral losses for Stuttgart for all technologies and a much lower difference between the spectral impact for different technologies. According to Dirnberger *et al.* one reason for this difference could rely on the fact that spectral models are limited in their ability to represent cloudy conditions.

However, it should be mentioned that since the studies published in these articles were realized, most of the solar cell technologies have shown a significant progress. For example, a recent study conducted by M. Schweiger and W. Herrmann of TÜV Rheinland[46] analyzed outdoor performance data of four different PV technologies in four locations around the world: Cologne, Germany; Arizona, United States; Anacona, Italy; and Chennai, India. The largest spectral gains for all technologies were observed in the humid climate of India, with CdTe showing a gain of 5.3%. In contrast, the dry climate of Arizona showed the highest spectral loss of -1.6% and -1.2% for a CIGS and a c-Si device, respectively. The European climates of Italy and Germany

[45] D. Dirnberger *et al*., "On the impact of solar spectral irradiance on the yield of different PV technologies," *in Solar Energy Materials & Solar Cells,* vol. 132 pp. 431–442, 2015.
[46] M. Schweiger and W. Herrmann, "Comparison of Energy Yield Data of Fifteen PV Module Technologies," *IEEE 42nd Photovoltaic Specialists Conference,* New Orleans (LA), US, 2015.

showed more moderate spectral adjustments; with lower values of 0.5% and 1.3% for c-Si, 0.7% and 1.8% for CIGS and 1.0% and 2.3% for CdTe, respectively. The spectral irradiance data, analyzed by the authors in a previous paper[47], showed a red shift in the solar spectrum in winter and a blue shift in summer. Overall, the results presented for the German test locations by Dirnberger *et al.* and TÜV Rheinland agree well, with a 2.4% annual spectral gain for CdTe compared to 2.3%, respectively, and a 1.4% annual spectral gain for c-Si compared to 1.3%, respectively.

***Soiling***

The sunny areas in the south of Europe are characterized by high airborne-particle environments, dust transportation by wind and reduced water availability. Significant soiling losses due to dust deposition have also been reported in Europe, especially in the southern and Mediterranean parts with losses ranging from 1% to 5% loss per year in Italy[48] to more than 10 % loss per month in Malaga, Spain[49] or absolute power losses of 43% in Cyprus[50]. Since power losses of more than 1% per day due to dust deposition on glass surfaces are reported for some of these regions[51], the soiling problem came into focus as one of the main concerns of system reliability[52,53,54]. Figure 25 shows the development of soiling on First Solar modules in a dusty environment at DEWA site (Dubai, UAE).


| Day | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|
| Loss | 2% | 2.3% | 2.7% | 3% | 3.3% | 3.5% |

**Figure 25** Field images of soiling accumulation on FS modules at DEWA site (Dubai, UAE)[55].

Consequently, First Solar identified soiling as “the 3rd most important PV performance factor,

[47] M. Schweiger *et al.*, “Energy yield of thin-film PV modules and the relevance of low irradiance, spectral and temperature effects,” in *IEEE 39th Photovoltaic Specialists Conference (PVSC), Part 2*, Tampa, Florida, US, 2013.
[48] A. Massi Pavan *et al*., “A comparison between BNN and regression polynomial methods for the evaluation of the effect of soiling in large scale photovoltaic plants,” *Applied Energy* vol. 108, S. pp. 392–401, 2013.
[49] M. Piliougine *et al*. “Comparative analysis of energy produced by photovoltaic modules with anti-soiling coated surface in arid climates,” *Journal Applied Energy*, vol. 112. pp. 626–634, 2013.
[50] S.A. Kalogirou *et al*., “On-site PV characterization and the effect of soiling on their performance,” *Energy*, vol. 51, pp. 439–446, 2013.
[51] A. Sayyah *et al*. ”Energy yield loss caused by dust deposition on photovoltaic panels,” *Solar Energy*, vol. 107, pp. 576–604, 2014.
[52] M. Mani and R. Pillai, “Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3124–3131, 2010.
[53] T. Sarver *et al*., “A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches,” *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 698–733, 2013.
[54] S. Costa *et al*., “Dust and soiling issues and impacts relating to solar energy systems. Literature review update for 2012–2015,” *Renewable and Sustainable Energy Reviews*, vol. 63, pp. 33–61, 2016.
[55] R. Bkayrat, “Lessons learnt with PV power plants in the US desert”, VP Business Development Saudi Arabia, 2013

behind only insolation and temperature"[54]. In various studies[54,56,57,58,59,60], First Solar investigated the effect of soiling, ranging from soiling monitoring evaluation to quantification of anti-soiling benefits of anti-reflective coatings (ARC). Figure 26 shows one example of an ARC study, where laboratory scale environmental simulators are correlated to real world performance data collected from field studies with test ARC modules and coated glass coupons.


**Figure 26** (left) Soiling monitoring station at test site in UAE. (right) Lab scale environmental simulator for anti-reflective coating development[59].

Besides mineral dust blown from Sahara[61] to Europe there are many other sources for soiling of PV modules, including agriculture (e.g. animal feed dusts, cattle breeding (ammonia)), industry (process dusts, exhaust), traffic (carbon particles, soot) and organics (pollen, seeds, bird droppings, leaves, lice, lichen, algae, moss). All of these effects are strongly dependent on location and the periodically cleaning cycles by wind and rainfall.

**Figure 27** Manual Dry Brush Trolley designed for First Solar modules from Aztera[62].

[56] L. Dunn, Lawrence *et al*., "PV module soiling measurement uncertainty analysis," *in IEEE 39th Photovoltaic Specialists Conference*, Tampa, Florida, S. pp. 658–663, 2013.
[57] J. Caron *et al*., "Direct Monitoring of Energy Lost Due to Soiling on First Solar Modules in California," *in IEEE J. Photovoltaics, vol.* 3, no.1, pp. 336–340, 2013.
[58] M. Gostein *et al.*, "Measuring soiling losses at utility-scale PV power plants," *in IEEE 40th Photovoltaic Specialists Conference*, Denver, Colorado, S. 885–890, 2014.
[59] M. A. Grammatico and B. Littmann, "Quantifying the Anti-Soiling Benefits of Anti-Reflective Coatings on First Solar Cadmium Telluride PV Modules," *in IEEE 43th Photovoltaics Spec. Conf*., Portland, OR, 2016.
[60] R. Bkayrat and M.A. Lewis "First Solar perspectives and experience on soiling and dust mitigation", DEWA & NREL 3 days workshop "Soiling effect on PV modules" 5-7/4/2016.
[61] C. Collaud, *et al.,* "Saharan dust events at the Jungfraujoch. Detection by wavelength dependence of the single scattering albedo and first climatology analysis," *Atmos. Chem. Phys*. Vol. 4 (11/12), pp. 2465–2480, 2004.
[62] AZTERA "Manual Dry Brush Trolley - Operational Instructions". Version 1.1, 2013.

At some locations effective cleaning strategy can be established in order to optimizing cleaning costs versus yield losses[63]. A huge variety of cleaning methods exist[64,65]. Beside effectiveness of the cleaning methods, their impact on the glass surfaces and coatings is very important, e.g. damage or abrade of anti-reflection coatings and subsequent power losses[66]. Therefore, First Solar created a cleaning guidelines for coated and uncoated modules as well as providing customized cleaning solutions like the "AZTERA Manual Dry Brush Trolley"[67,62].

#### 2.2.2.3.- Grid integration

PV electricity is taking over a steadily growing share of energy distributed in European electricity networks. For example, in Germany a large fraction of electricity during peak load day time is generated from solar modules in residential and utility-scale PV power plant installations. The integration of utility-scale solar PV generators in the electricity grids represents, at the same time, opportunities and challenges in relation to regional conditions. As PV power plants provide a significant contribution to the electricity grid, they can also support grid stability and reliability as a whole.

Dynamic voltage regulation, active power management, ramp-rate control, frequency droop control and fault-ride-through capability are all aspects related to grid-friendly PV plants that are operational today[68]. Figure 28 shows a schematic diagram with an example of a plant control system and interfaces to other components.

The plant controller provides the following plant-level control functions:

- Dynamic voltage and/or power factor regulation of the solar plant at the point of interconnection (POI)
- Real power output curtailment of the solar plant when required, so that it does not exceed an operator-specified limit
- Ramp-rate controls to ensure that the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible
- Frequency control to lower plant output in case of over-frequency situation or increase plant output (if possible) in case of under-frequency
- Start-up and shut-down control

[63] P. Sinha *et al*., "Life cycle materials and water management for CdTe photovoltaics," *Solar Energy Materials & Solar Cells,* vol.119, pp. 271-275, 2013.
[64] A. Sayyah *et al.,* "Energy yield loss caused by dust deposition on photovoltaic panels," *Solar Energy* 107, pp.576–604, 2014.
[65] A.K. Mondal and K. Bansal, "A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels," *Advanced Robotics, vol.* 29, no. 8, pp. 515–524, 2015.
[66] N. Ferretti *et al*. "Investigation on the Impact of Module Cleaning on the Antireflection Coating,*" in 2nd European Photovoltaic Solar Energy Conference and Exhibition,* 2016.
[67] First Solar "FS-Series PV Module Cleaning Guidelines", 2014.
[68] M. Morjaria, "A grid-friendly plant", *IEEE power & energy magazine*, pp. 87-95, 2014.

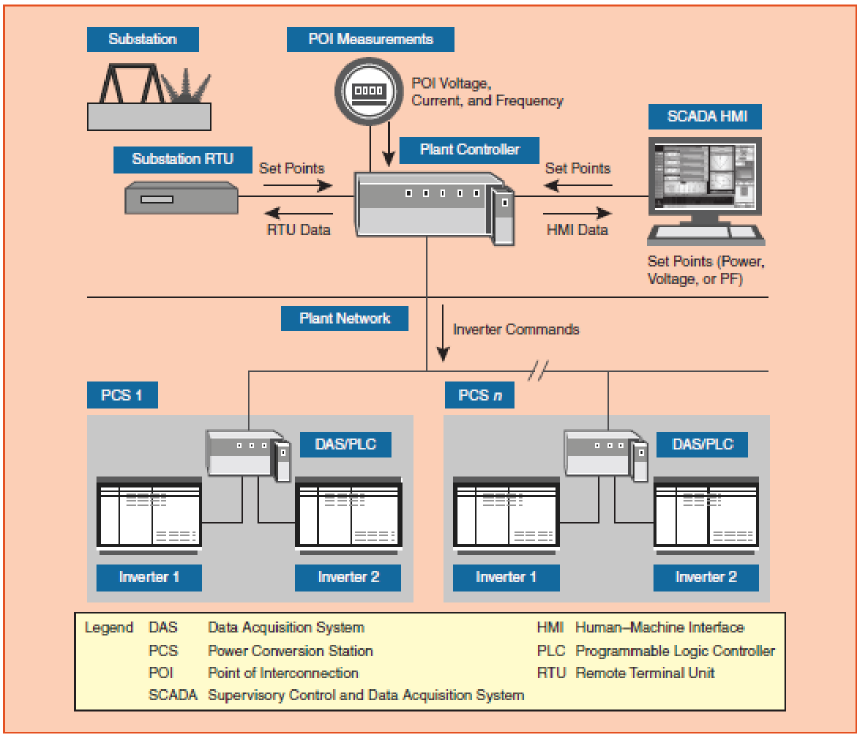



**Figure 28** Example of a plant control system and interfaces to other components[68].

Figure 29 left shows an example of a large utility-scale, 290 $MW_{ac}$ CdTe PV module, power plant controlled from a grid-friendly plant control center. First Solar owns and operates a Solar Operations Center in Tempe (AZ) (Figure 29 right), from which it currently monitors the performance of over 2,000 MWp of CdTe PV power plants in the USA.

**Figure 29** (left): First Solar's Yuma County-Arizona, 290 MWp CdTe PV power plant with grid-friendly plant control and (right) Operations Center in Tempe, Arizona, controlling over 2,000 MWp of solar power plants operating in the USA[69].

In summary, various advanced capabilities have been incorporated within First Solar's concept of utility-scale, grid-friendly PV power plant. PV system parameters like voltage, active power ramp-rate and frequency are controlled by a central plant-level controller. A reliable plant

[69] M. Morjaria and D. Anichkov, 'Grid-Friendly' Utility-Scale PV Plants. Transmission & Distribution World, August 14, 2013. http://tdworld.com/generation-renewables/grid-friendly-utility-scale-pv-plants

operation in the grid has been evaluated with Western Electricity Coordinating Council (WECC) guidelines for the general structure and behavior of power plants.

# 2.3.- EH&S ASPECTS OF FIRST SOLAR'S CdTe TECHNOLOGY

In this section Environmental, Health and Safety (EH&S) aspects of First Solar's CdTe PV module manufacturing technology, during their normal operation as well as end-of-life disposal will be analyzed. As an introduction, a short overview of First Solar's CdTe manufacturing and recycling processes are presented including a description of CdTe chemistry and toxicology and raw material sourcing.

## 2.3.1.- CdTe CHEMISTRY AND TOXICOLOGY

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 Cd has a silver grey metallic color with a melting point of 321 ºC and a boiling point of 765 ºC. Cd is found in the earth's crust in zinc ores, as cadmium sulfide. On the other hand, tellurium is a very rare semi-metal, extracted mainly as a by-product from copper and lead ores.

Cadmium telluride, used for photovoltaic applications, is a synthetic black solid 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[70]. Although sublimation occurs, CdTe vapor pressure is 0 at normal conditions and is only 2.5 torr (0.003 atm) at 800 ºC[71]. CdTe has an extremely low solubility in water (CdTe solubility product $9.5x10^{-35}$ mol/L compared with Cd solubility product 2.3 mol/L) but is dissolved in oxidant and acidic media. It may decompose on exposure to atmospheric moisture being able to react with water and oxygen at elevated temperatures[71], as utilized in First Solar's module recycling process (see section 2.3.2.3.-). CdTe, with a water solubility value of 19 µg/L, is classified as insoluble in water by ECHA (limit < 0.1 mg/L)[72].

CdTe differs from elemental Cd in that it is a strongly bonded compound with an extremely high chemical and thermal stability, which limits its bioavailability and its potential for exposure to humans and the environment. The most recent toxicology studies on CdTe with respect to Cd and other Cd substances concluded that:

- For CdTe, the median lethal concentration (LC50) and dose (LD50) is more than 3 orders of magnitude higher than that of Cd with respect to acute inhalation and oral toxicity[73].

[70] P. Moskowitz, *et al.*, "Environmental health and safety issues related to the production and use of cadmium telluride photovoltaic modules," *Advance in Solar Energy*, vol.10, Chapter 4, 1990, American Solar Energy Society, Boulder CO.
[71] "DOE and BNL Nomination of CdTe to the NTP", April 11, 2003.
[72] https://echa.europa.eu/de/registration-dossier/-/registered-dossier/12227/4/9
[73] P. Zayed and S. Philippe, "Acute oral inhalation toxicities in rats with cadmium telluride," *International Journal of Toxicology*, vol 28, no. 4, pp. 259-265, 2009.

- Previous results have been summarized by Kaczmar[74] regarding mutagenicity, acute aquatic toxicity and acute inhalation and oral toxicity data for CdTe, Cd and other Cd compounds. He concluded that CdTe has a margin of safety of two orders of magnitude using the read-across approach from Cd, (Figure 30).
- These results are also supported by the latest results by Kounina[75] in which, the CdTe characterization factor is also around 3 orders of magnitude lower than Cd(II), this is attributed to a lower effect factor of CdTe ($3.74x10^2$ $kg^{-1}·m^3$) than for Cd(II) ($3.3x10^4$ $kg^{-1}·m^3$) .

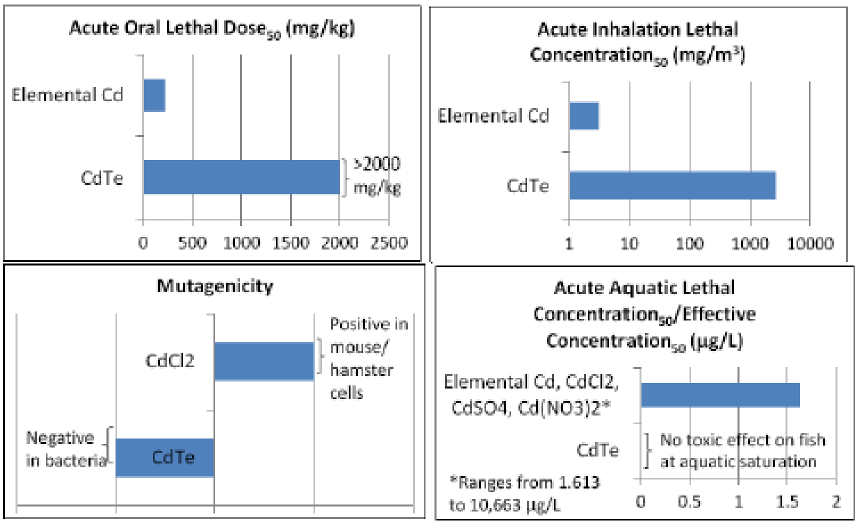



**Figure 30** Comparative toxicity between Cd, other Cd compounds and CdTe.

In this regard, the European Chemicals Agency (ECHA) Globally Harmonized System (GHS) does not include CdTe ingestion and skin contact pathways in the hazard statement. CdTe is classified as harmful if inhaled and the toxicity classification to aquatic life has been reduced from very harmful to harmful[72].

In the EU, the exposure limit values vary among the Member States. In the ECHA Dossier[72] values and/or specific regulations are included for Austria, Denmark, France, Germany, Hungary, Spain, Sweden, Switzerland and the United Kingdom.

## 2.3.2.- CdTe MODULE MANUFACTURING PROCESSES

### 2.3.2.1.- Raw materials

First Solar's module manufacturing technology uses a black CdTe powder as starting raw material that is supplied by a third party.

Although the identity of most suppliers is considered by First Solar to be confidential information, First Solar's semiconductor supplier (5NPlus) has facilities in the EU, North

[74] S. Kaczmar, "Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics," *Society of EnvironmentalToxicology and Chemistry (SETAC)*, North America, 32nd Annual Meeting, 2011
[75] A. Kounina, *et al.*, "Provision of USETox Characterization factor for CdTe", Quantis 2016.

America, and Asia and is certified to OHSAS 18001 Health and Safety Management System, ISO 14001 Environmental Management standards, and ISO 9001 Quality standards.

For all Cd related suppliers, including products and services, like waste disposal facilities, First Solar undergoes environmental audits performed by themselves or by external consultants. First Solar shares EH&S best practices with their suppliers to help them achieve a higher performance profile on environmental, health and safety aspects. The Company performs periodic reviews of critical suppliers using a balanced scorecard focused, among others, on quality, service, technology and sustainability.

In 2014, approximately 12.5% of the Te in the semiconductor came from recycled materials. According to First Solar's data and strategy[76], raw materials (Cd and Te) availability in combination with improvements in semiconductor intensity and recycling can enable future production of 100 GW per year of CdTe PV modules[76].

#### 2.3.2.2.- Process flow

CdTe PV module manufacturing flow encompass three main steps: The first one corresponds to the semiconductor material deposition; secondly, PV cells and cell interconnections are defined; and finally, the module assembly and test is performed. First Solar's CdTe PV module fabrication cycle time is less than 2.5 hours.

The manufacturing process starts with the deposition onto a glass substrate of a thin tin oxide layer that serves as a transparent and conductive contact (TCO). Then, a very thin layer of CdTe (absorber) is deposited. First Solar's CdTe PV modules manufacturing technology is based on the sublimation property of CdTe. As the material is heated, CdTe sublimes to yield gaseous Cd and Te that are re-deposited onto the substrate[77]. The company uses a vapor transfer deposition (VTD) technique that has the advantages of high deposition rates compared to other techniques like closed-space sublimation (CSS). Next, a thermal treatment, in the presence of $CdCl_2$, is performed to improve the electronic properties of the device. Note that $CdCl_2$ is an intermediate substance, which is not to be found in the final product. Finally, a metal layer, using sputtering techniques, is deposited to create the back contact.

The individual photovoltaic cells are interconnected in series using a laser scribe technology, followed by a lamination process where an intermediate polymer foil and a glass, as back cover, are placed and thermally sealed together with the glass substrate.

[76] First Solar Sustainability Report 2016.
[77] D. Bonnet and P. Meyers, "Cadmium-telluride—Material for thin film solar cells," *J. Mater. Res.* vol.13, no. 10, pp. 2740-2753, 1998.

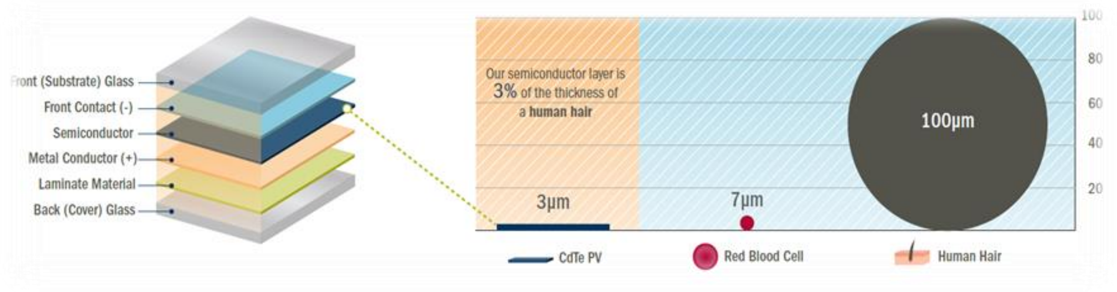



**Figure 31** Schematic representation of First Solar's module architecture[76].

As it is depicted in Figure 31, very little amount of CdTe is used in a module. As a comparison, the semiconductor layer is 3% of the thickness of a human hair.

#### 2.3.2.3.- Recycling process

First Solar's recycling process begins with the modules being reduced in a twostep process. In a first step, a shredder breaks the module into pieces, while step two uses a hammer mill 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. The bulk of the plastic interlayer encapsulation foil is separated at this stage, and the whole process is operated under strict control of dust and aspiration with high efficiency particulate air (HEPA) filters.

The module fragments are then leached with an acidic oxidizing solution ($H_2SO_4$ + $H_2O_2$) to solubilize the Cd and Te cations; this step has evolved from the original use of small (1,000 modules/day) rotary leaching reactors to today's larger (15,000 modules/day) and more efficient stationary reactors. The leaching solution is also recycled a number of times, thereby reducing reagent consumption. The remaining fragments of the encapsulation foil are physically separated from the glass by a vibrating screen, and the recovered glass is then rinsed in a form which is pure enough for most commercial uses. At the same time, the Cd and Te are precipitated as $Cd(OH)_2$ and $H_2TeO_3$ / $Te(OH)_6$ by adding NaOH to increase the pH of the solution, and the precipitate is then dewatered by filter pressing to produce the so-called "filter cake", while the remaining solution is sent to wastewater treatment. The filter cake is finally sent to a partner company where it is reprocessed into semiconductor-grade CdTe for use in new PV modules[78] (Figure 32).

According to First Solar's recycling technology information, approximately 90% of the module weight is recovered most of it being glass that can be used in new glass products. The achieved recovery of the semiconductor material is over 90%[79,80]. The remaining 10% is treated as hazardous waste (see section 2.3.2.3.- manufacturing by-products) and is disposed in accordance with local laws.

[78] S. Raju, "First Solar Recycling & WWT Program Overview,", Perrysburg site visit, June 2016
[79] M. Held, "Life cycle assessment of CdTe Module Recycling," in *24th EU PVSEC Conference*, Hamburg, Germany.
[80] P. Sinha and M. Cossette; "End-of-Life CdTe PV Recycling with semiconductor refining *" In Proceedings 27th EU PV SEC,* Frankfurt, Germany, 2012.

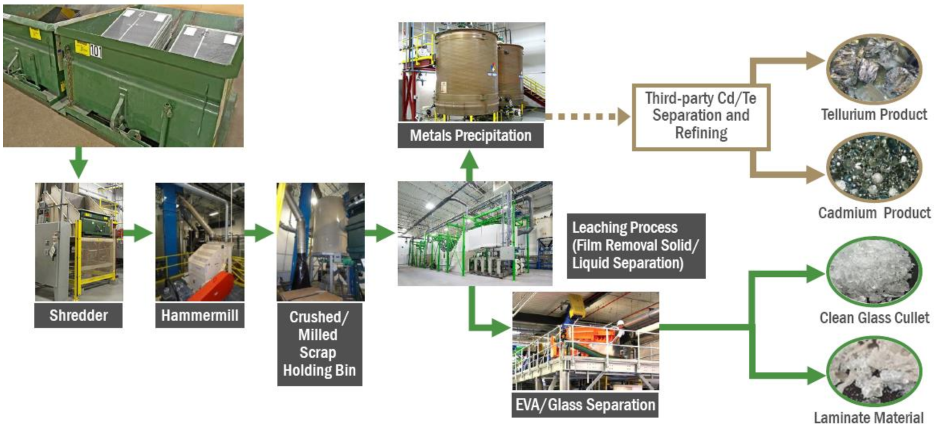



**Figure 32** Flow chart of CdTe PV module recycling process[78].

According to First Solar's documentation, the recycling technology has evolved since 2006 from version V1 to V3. Leaching reactor efficiency, volume output, flexibility for capacity expansion and cost reduction are the main improvements achieved in the recycling process over time. The company has several on-going projects to further improve the recycling technology and they aim to develop a mobile recycling plant by 2027.

First Solar has operational recycling facilities in Perrysburg (OH, US), Kulim (Malaysia) and Frankfurt-Oder (Germany) with a total annual recycling capacity of approximately 2 million modules.

### 2.3.3.- EH&S POLICIES FOR MODULES MANUFACTURING

EH&S aspects like safety first, environmental responsibility and people matter have been defined by First Solar as core values for the Company. To that end, the Company has established an EH&S management system to eliminate or minimize the risk to employees or other parties who may be exposed to manufacturing activities. All First Solar manufacturing sites are certified to OHSAS 18001 Health and Safety Management, ISO 14001 Environmental Management and ISO 9001 Quality standards.

First Solar has fostered a strong EH&S culture to ensure a safe workplace for all employees. They have in-staff experts in all the disciplines related to EH&S aspects. The Company is very active in developing and improving safety programs, encouraging the participation of the inline staff as well as management personnel. The strategy for new facilities is based on the "copy exact" philosophy with regards manufacturing technology, policies, practices and management systems. This helps to minimize the risk of schedule, cost, environmental, health and safety issues, while guaranteeing product quality and uniformity.

#### 2.3.3.1.- Manufacturing and recycling

First Solar's CdTe PV modules manufacturing and recycling operations involve Cd and other Cd compounds that are present, either in gas-phase (dust and fumes) or dissolved in water, in several steps of the manufacturing sequence as well as in maintenance operations. Modules recycling capability is included in all First Solar's facilities as a standard production process, therefore, the same environmental, health and safety protocols used in the modules manufacturing are implemented to protect workers from CdTe dust produced in the recycling processes.

First Solar has implemented a Cadmium Management Program in all manufacturing sites with a continuous and effective control of the Cd concentration in indoor air and emission to the environment and wastewater.

First Solar has developed a “Cadmium Exposure Assessment” that encompasses the following aspects:

- A qualitative exposure assessment that is certified by an external party
- A quantitative exposure assessment that includes an external party certification and an exhaustive Cd sampling plan developed internally
- A ventilation assessment that is also certified by an external party and an in-depth protocol to test the HEPA filters and ventilation systems
- A medical surveillance program that monitors potential worker exposure to Cd through biological monitoring

First Solar’s Industrial Hygiene Management Program for Cd management includes air sampling for personal area and equipment, medical surveillance for 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.

First Solar has a world-class design and operation system to control Cd emissions to the indoor air and to the environment in all their manufacturing facilities. All process equipment involving Cd are 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 per international standard IEST-RP-CC00342 to ensure capture efficiency. 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. First Solar performs a global air sampling analysis quarterly.

The occupational exposure limit (OEL) for Cd has been established by the US regulatory agency at 5 $\mu g/m^3$ and 3.33 $\mu g/m^3$ for 8 hours and 12 hours exposure respectively. First Solar action limit is set at 1 $\mu g/m^3$ for its U.S. and Malaysia facilities and the actual indoor air values range from (0.006 to 0.35)[81] $\mu g/m^3$ in normal operation, well below the OEL.

In the commercial recycling facility in Germany, Cd indoor air are measured on a quarterly basis and during facility downtime/startup at task-specific locations such as shredder, hammer mill, leaching drums, screw conveyer. Cd concentrations are below 0.16 $\mu g/m^3$.

[81] L. Kraemer, “Safety, Industrial Hygiene and Occupational Health”, Perrysburg site visit, June 2016

The recycling facility in Germany was built in 2007 in the same facility as the manufacturing operation and under the umbrella of the EH&S department. The facility has been subjected to various audits: ISO (9001/14001) and OSHA (18001) standards, as well as audits related to its certificate as a waste handling facility (*Entsorgungsfachbetrieb*). All these audits validate a legally compliant management and operation system that includes health and safety. Additional to these audits, governmental authorities (*Amt für Arbeitsschutz, Wasserbehörden, Berufgenossenschaft, Landesamt für Umwelt und Verbraucherschutz* etc) periodically observe the recycling plant.

Besides First Solar global EH&S guidelines (i.e. Cd-Compliance plan, Logout/Tagout-, confined space-, electrical safety- programs, EH&S database tracking) a local legal requirement relates to risk and/or job hazard analysis which is a main tool of First Solar EH&S. The recycling plant in Germany has a CE. This is based on risk analysis for the plant equipment to demonstrate that state-of-the-art safety concepts and regulations are met for the equipment. The recycling plant is a permitted (BImSchG) recycling facility.

First Solar has an active medical monitoring program for their employees to ensure that their industrial hygiene practices are effective. Recent Medical monitoring results[82] compared from nearly 3,000, of Malaysia facility workers over a period of 5 years, showed that Cd levels in blood and urine are well below the threshold level established by OSHA (Cd in urine (CdU), standardized to grams of creatinine (g/Cr) ≤ 3 µg/g Cr and Cd in blood (CdB), standardized to liters of whole blood (lwb) ≤ 5 µg/lwb). These results also show a statistically significant decreasing trend for Cd levels in blood and urine as a function of years worked for non-smokers, most likely due to the improved background of public health conditions in Malaysia. Similar results are found in Perrysburg (OH, US) and Frankfurt/Oder (Germany) facilities.

#### 2.3.3.2.- Manufacturing by-products

During CdTe PV module manufacturing and recycling operations, dust, fumes and water containing Cd, Te and CdTe are generated as by-products. These by-products produce three different types of wastes: air exhausted to the environment, wastewater and solid wastes.

***Air emissions***

First Solar has a state-of-the-art HEPA filter control system, as has been described earlier, that leads only to a 0.0001% of the incoming Cd emitted into the air. A measurement carried out by the independent NM Laboratory Sdn. Bhd. in Kulim (Malaysia) disclosed that: *"the air impurities and solid particles concentration emitted from the chimneys of Building KLM 5 on March 5th 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"*[83]. The latest air emissions measurements performed by First Solar[84] in their Perrysburg facility in 2015, shows that Cd emissions to air are $9.56x10^{-9}$ kg/m$^2$ of module produced, well below the regulatory limits. First

[82] P. Sinha *et al*., "Biomonitoring of CdTe PV Manufacturing Workers," *IEEE PVSC*, Portland, 2016.
[83] NM Laboratory Sdn. Bhd. 2013. Air Emissions Monitoring Report, AEMR/13-03/46
[84] First Solar 2016 "First Solar Series 4 PV System Product Environmental Footprint".

Solar estimates that the total Cd emissions to air for a 100 MW/yr manufacturing facility are less than 6 g/yr.

***Wastewater***

First Solar's wastewater treatment process flow includes operations like metals precipitation, filtration and ion exchange polishing. A continuous checking is performed of the Cd content in the water before it is approved for discharge. If the wastewater is out of specifications, it is re-circulated through the wastewater treatment system.

These processes reduce Cd levels in wastewater to less than 20 ppb (typical value is 10 ppb) at all First Solar manufacturing facilities.

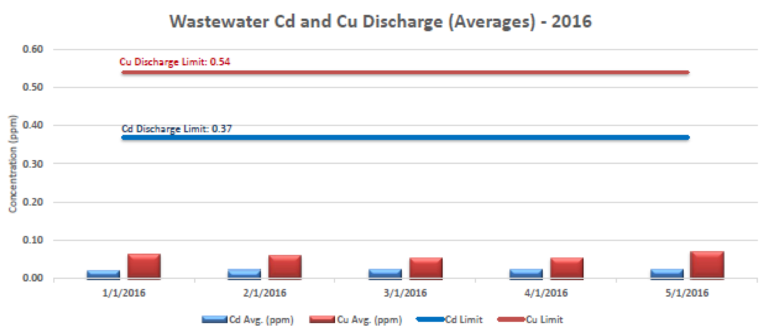



**Figure 33** Wastewater Cd and Cu concentration[78].

Figure 33 shows the current Cd and Cu concentration in wastewater together with the discharge limits. As it can be observed, both are significantly below the permitted discharge limits established at 0.37 ppm for Cd and 0.54 ppm for Cu. Independent wastewater measurements are also performed by NM Laboratory Sdn. Bhd. at Kulim facility[85].

***Solid wastes***

During manufacturing and recycling operations, hazardous solid wastes are also generated including used HEPA filters, waste from maintenance operations, ion exchange resins, semiconductor materials from recycling etc. According to First Solar[76], these wastes represent less than 10% of the total solid manufacturing waste and are classified following the definition used by the countries in which First Solar operates and disposed accordingly with local regulations.

Unrefined semiconductor material is sent to 5NPlus for further processing to be reused in new modules. HEPA filters are also sent to third parties for disposal as hazardous waste and ion exchange resins stay within the system, as they are regenerated and used again.

First Solar's semiconductor supplier has a management system to track waste minimization, resource conservation, and recycling[81].

[85] NM Laboratory Sdn. Bhd. 2013. Test Report WA1305-1232-1

## 2.3.4.- EH&S ASPECTS DURING MODULE OPERATION

In accordance with the Low Voltage Directive 2014/35/EU, First Solar has conducted an internal assessment of product-related risks during module operation associated to electrical and mechanical hazards, by confirming that relevant hazards are addressed by aspects of the harmonized product safety standard (EN 61730) to which First Solar PV modules are certified. In the case of other hazards such as those related to emissions of hazardous substances and associated chemical effects, these risks are characterized in the studies described in this section.

In the present section the main Environmental, Health, and Safety aspects (EH&S) of First Solar's CdTe PV modules during normal operation are analyzed, including the potential risks regarding foreseeable accidents. Besides, EH&S aspects of non-intended uses, including uncontrolled disposal, and improper recycling are examined. In the following table, a list of the possible risk situations and the section of the present report where they have been studied are presented.

| Risk | Section where it is covered |
|---|---|
| **Emissions due to fire** | 2.3.4.1.- |
| **Leaching from broken modules** | 2.3.4.1.- |
| **Non-intended uses** | 2.3.4.2.- |
| **Uncontrolled disposal** | 2.3.4.2.- |
| **Improper recycling** | 2.3.4.2.- |

**Table 4** Risk scenarios related to CdTe PV module operation and their end-of-life, and sections in the present report where they have been covered.

The studies of fire and leaching from broken modules have considered rooftop as well as ground mounted applications. The non-intended uses, uncontrolled disposal, and improper recycling investigations, can also apply to both types of installations.

### 2.3.4.1.- Normal operation and foreseeable accidents

In this section the potential risks from the point of view of EH&S of First Solar's modules during normal operation and also aspects regarding foreseeable accidents, which include fire and breakage from which leaching can occur, are analyzed and discussed. This analysis is based on an independent review of the publicly available literature.

Operation is defined starting from the moment the production of the module is completed and ready for shipment, until the module is decommissioned and sent for recycling or disposal. During the operation period CdTe PV modules will undergo the following situations:

- Module transportation from manufacturing plant to customer's site.
- Module installation on final location.
- Operation of modules.
- Modules decommissioning and/or collection.
- Transportation of modules to the recycling plant or to landfill.

During normal operation, First Solar's CdTe modules do not pose any environmental or health risk since no emission of hazardous materials occurs. The CdTe semiconductor layer is encapsulated in between laminate material and glass. In these conditions, no vapors or particulates containing Cd can be released. First Solar provides 25 years power output guarantee and therefore, the modules will be installed in the field at least for that time.

Two situations in which Cd could potentially be released to the environment from CdTe PV modules during foreseeable accidents have been identified. These two situations include the possibility of fire events and breakage of CdTe PV modules and are analyzed in the following paragraphs.

***Cd emissions due to fire***

Fire events involving PV modules are very rare. According to Prume *et al*[86], in Germany a total of 210 fire events, over 1.3 million PV installations, had been reported as of January 2013, where the PV installation was the root cause for a fire. PV modules subjected to fire release several substances such as $CO_2$, CO, water, acetic acid, and heavy metals, which are part of their composition. Regarding the release of Cd due to a fire event involving CdTe PV modules, several scientific studies have tackled the question. In the following paragraphs the results and conclusions extracted from the most relevant scientific contributions are reviewed.

In general, modules can be exposed to building or vegetation fires, thus affecting roof or ground mounted modules. The predominant application of CdTe PV modules is in large commercial and utility scale power plants reaching from several 100s of kW to several 100s of MW. First Solar operates a business model in which the modules are exclusively used in these kind of large scale projects and residential rooftop applications are not foreseen.

In the case of utility scale power plants, site preparation, operation and maintenance activities limit on-site vegetation that typically consists of grass. For grass fires, flame residence times in grass fuels are approximately 15 seconds, and maximum temperatures are approximately 800 ºC to 1000 °C[87]. In comparison, the melting point of CdTe is 1041°C, and the melting point of module glass is several hundred degrees centigrade higher[88]. Therefore, for ground mount systems exposed to grass fires, Cd would remain encapsulated in the modules.

[86] K. Prume, "Bewertung des Brandrisikos in Photovoltaik-Anlagen und Erstellung von Sicherheitskonzepten zur Risikominimierung," TÜV Rheinland Energie und Umwelt, March 2015. This report was translated into Spanish by the Chilean *Ministerio de Energía*, and is available at http://www.pv-brandsicherheit.de/8/.
[87] D. L. Martell, "Grass fire behavior and flame," retrieved May 5, 2010, available at http://www.firelab.utoronto.ca/behaviour/grass_fire.html.
[88] P. Sinha *et al*., "Fate and transport evaluation of potential leaching and fire risks from CdTe PV," in *37th IEEE Photovoltaic Specialist Conference*, Seattle, WA, pp.002025-002030, 2011.

With respect to rooftop applications, the first experimental study regarding the determination of the amount of Cd that can be released in a fire event involving CdTe PV modules was performed by Fthenakis *et al*[89]. This experiment was set up to follow the standard temperature rate curve described in the ASTM Standard E119-98 for Fire Tests for Building Construction and Materials and UL Protocols, but no fire flame was applied to the CdTe samples. The experimental procedures were carefully implemented in order to collect and analyze all the Cd and Te releases (fumes and solid residues deposited in the reactor walls). According to this experiment:

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

In a fire, the EVA laminate burns or decomposes at approximately 450 ºC and glass softening occurs at 715 ºC. The experiment was performed with 25 cm x 3 cm samples, without any CdTe edge exclusion, which is not the actual First Solar's CdTe modules configuration. Adjusting for this loss in full-size modules, results in 99.96% retention of Cd. Besides, Fthenakis considered Cd emissions to be zero in ground mounted installations due to the lack of combustible materials in this situation.

In 2011 Sinha *et al*.[88] performed fate and transport analysis to calculate the Cd emissions from fires taking into account releases to ambient air and transport to soil and groundwater from water used to extinguish the fire. Fate and transport analysis simulate how chemicals degrade and travel in the environment when they are released. In this contribution three different fire sizes (i. e. small, medium, and large buildings) involving roof mount CdTe PV modules were modelled. To perform the fate and transport calculations, the total mass of Cd released from a module array during a fire was estimated from the number of modules in the array and the Cd release efficiency experimentally measured by Fthenakis (0.04%). Inhalation risk to workers, residents, and emergency responders was evaluated by comparing exposure point concentrations from the fate and transport analysis against the acute exposure guidelines (AEGLs)[90]. The AEGLs represent the threshold exposure limits for the general public and are applicable to emergency exposure periods ranging from 10 minutes to 8 hours. With regard to the affected soil and groundwater in the fire scenario, risk-based screening levels of Cd in soil were based on potential exposures via soil ingestion, soil dermal contact, and dust inhalation. Risk-based screening levels of Cd in groundwater were based on potential exposures via

[89] V. M. Fthenakis *et al.*, "Emissions and encapsulation of cadmium in CdTe PV modules during fires," *Progress in photovoltaics: Research and applications*, vol. 13, no. 8, pp. 713-723, December 2005.
[90] USEPA, "Acute Exposure Guidelines (AEGLs) for Cadmium 7440-43-9 (Interim)", https://www.epa.gov/aegl/cadmium-results-aegl-program, last access date 02/08/2016.

drinking water ingestion, dermal contact with tap water while showering, and inhalation of tap water aerosols while showering. According to the results obtained in this work, and for the three different fire sizes, all estimated exposure concentrations were below conservative screening values, generally by one or two orders of magnitude. Incremental cancer risks associated with short-term exposure to Cd were also evaluated in accordance with USEPA inhalation risk assessment methodology[91]. Estimated cancer risks were over an order of magnitude below the 1 in 1 million level considered by USEPA to be the risk screening threshold.

Also in 2011, the Bavarian Environmental Protection Agency calculated the emissions of Cd and oxide fumes (CdO and $TeO_2$) during fires of photovoltaic modules containing CdTe[92]. In this study, it was assumed that in the calculations all Cd contained in the module was released completely from the CdTe compound as Cd fumes. Even under a worst-case scenario with a fire involving 1000 $m^2$, maximum Cd module content of 66.4 $g/m^2$ (which is an order of magnitude higher than commercially CdTe PV panels produced today), and a distance of 100 m, the calculated Cd emissions were below AEGL-2/ERPG-2 levels (which correspond to irreversible or other serious, long-lasting adverse health effects or an impaired ability to scape). It was therefore concluded that a serious danger for the immediate neighborhood when CdTe modules burn was negligible. Emergency responders might get much closer than 100 m to the fire point, as evaluated in Sinha *et al*. 2011[88], where conservative fate and transport analysis showed that the exposure point concentrations were generally one to two orders of magnitude below conservative screening values. Nevertheless, it should be mentioned that the main risk for firefighters in the extinction of a fire involving PV modules is related to the possibility of suffering an electrical shock. In this respect, many countries have developed protocols to guide firefighters when extinguishing fires involving PV modules.

In a study published in 2014, the German *Bundesanstalt für Materialforschung und Prüfung (BAM)* conducted experiments to investigate the behavior of different PV technologies and the potential release of hazardous substances in a real fire event[93]. In this study, different types of fire tests were applied to whole CdTe PV modules and also to smaller samples obtained from CdTe PV modules. More specifically, fire tests following German DIN 4102-1, ISO 5659-2, and ISO 5660 were applied to full modules, and samples of 75 mm x 75 mm and 50 mm x 50 mm sizes, respectively. CdTe samples were affected by multiple glass cracks after the effects of both ISO-based fire tests. The samples after the fire test were analyzed showing that most of the Cd remained in the molten glass in percentages between 94% - 100%. In general, the glass/glass configuration, which included CdTe PV modules, proved to be more fire resistant, with a lesser amount of flaming droplets and less smoke production than the modules with the

[91] USEPA, "Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment)", Office of Superfund Remediation and Technology Innovation, 2009.
[92] J. Beckmann, "Calculation of immissions in case of fire in a photovoltaic system made of cadmium telluride modules," Bavarian Environmental Protection Agency, 2011.
[93] S. Krüger *et al*., "Systematische Untersuchung des Brandverhaltens und des Feuerwiderstandes von PV-Modulen einschliesslich der Emissionen im Brandfall und Entwicklung eines Prüfverfahrens zum Einfluss von PV-Modulen auf die harte Bedachung," German Bundesanstalt für Materialforschung und Prüfung (BAM), Berlin, Germany, ISBN 978-3-8167- 9248-2, 2014.

glass-backsheet configuration. This study provided valuable experimental information regarding the behavior of PV modules and the release of hazardous substances in case of a real fire event.

The most recent contribution to the investigation of Cd emissions in case of fire involving CdTe PV modules was undertaken by TÜV Rheinland Energie und Umwelt *et al*. in 2015[86]. The results were part of the BMWi research project "*Bewertung des Brandrisikos in Photovoltaik-Anlagen und Erstellung von Sicherheitskonzeptenzur Risikominimierung*". In this study, real fires were applied to crystalline Si, CdTe, and CIS modules in the Fire Research Laboratories of CURRENTA in June 2014, and the release of hazardous substances from the PV modules was characterized. The modules mounted on a tilted structure (23º), were exposed to real fires from the rear by means of a gas burner to simulate a potential rooftop fire scenario. The modules were exposed to two fire intensities, namely one with a heat power of 25 kW and a second and more intense one of 150 kW, in order to simulate hazardous substance release under different thermal conditions. Besides, a third experiment using a 150 kW gas burner, which fire was extinguished after 6 to 7 minutes using 20 liters of water over a period of 45 s was conducted. Temperatures were measured, but they were not included in the report and for this reason it is difficult to evaluate if these experiments represent real fire events. In all the cases, the harmful substances present in the flue gas and the fire residues were analyzed. In the case water was used to extinguish the fire, it was also analyzed. According to the data provided in this study of emissions to air of (19-43) mg Cd per CdTe PV module, and assuming 6 g of Cd content per module, the percentage of Cd emissions to air ranged from 0.3% to 0.7%, which is comparable to the results from Fthenakis *et al.* of 0.5%. In sum, the experimental fire testing from Fthenakis *et al*., BAM, and CURRENTA confirm low air emission rates of Cd from CdTe PV modules during fire, and the calculations from the Bavarian Environmental Agency, and Sinha *et al*[88] confirm that downwind Cd air concentrations are below acute exposure guideline levels. Because most of the Cd content is not being emitted to air and is remaining in the module and module debris, it was recommended to accordingly dispose the contaminated residues and replace the soil, which is a normal procedure following building fires. With regard to the fire water analysis, it was reported to contain (0.14-1.1) mg Cd per CdTe PV module. These values are slightly lower than the value for Cd mass release (2.4 mg Cd per CdTe PV module based on Fthenakis *et al.* emission rate) in the fire water scenario of Sinha *et.al*[88]. Therefore, similar fate and transport conclusions for soil and groundwater impacts are expected, as in Sinha *et al*., which could be confirmed with soil analysis as recommended in the CURRENTA study.

In the following table, the main parameters and results extracted from the scientific studies addressing the Cd emissions from fire incidents are summarized.

| Author | Type of experiment | Fire duration | Cd release |
| --- | --- | --- | --- |
| **Fthenakis *et al.* (2005)** | Furnace heat following ASTM E119-98 | 240 minutes | 0.5% |
| **S. Krüger *et al.* (2014)** | Burning Brand Test IEC 61730-2, Class A (wooden brand of 2 kg, wind speed 5.3 m/s) | - | 6.0% |
| | ISO 5659-2 (50 kW/$m^2$) | 14-17 minutes | 0.0% |
| **K. Prume *et al.* (2015)** | Gas burner of 25 kW | 30 minutes | 0.3% (to air)<br>0.0% (to solid residue) |
| | Gas burner 150 kW | 20 minutes | 0.7% (to air)<br>20.8% (to solid residue) |
| | Gas burner 150 kW; fire was extinguished after (6-7) minutes using 20 L of water during 45 s | 10 minutes | 0.5% (to air)<br>0.0% (to solid residue)<br>0.01% (to water) |
| **Sinha *et al.* (2011)** | Fate and transport analysis | - | Exposure concentrations below screening values |
| **Beckmann *et al.* (2011)** | Calculations; fire areas of 50 $m^2$, 500 $m^2$ and 1000 $m^2$ | - | Cd emissions to air below AEGL-2 levels |

**Table 5** Summary of key findings from main studies investigating Cd emissions from fire events involving CdTe PV modules.

As can be appreciated from the fire durations summarized in Table 5, the case of grass fires affecting ground mount systems, with flame residence times as short as approximately 15 seconds, represent a less critical situation for the emission of Cd than the experimental investigations reviewed in this section.

***Leaching risk in damaged CdTe PV modules***

Under normal operation of CdTe PV modules, there are no emissions to air, soil or water. Leaching of Cd can only occur in the event of broken modules or modules with defective laminations being subjected to the effect of acidic rainwater. Leaching from CdTe PV modules is an important matter since it could expose soil, air, or groundwater to Cd.

In a leaching process, the media environment conditions, such as pH, redox potential, leaching time, sample surface and liquid/solid ratio are very relevant, since they may affect the solubility of the materials. Leaching tests have typically been designed either for the identification of contents or waste characterization for landfill disposal, and are usually more aggressive than operating field conditions encountered by CdTe PV modules[94].

According to First Solar's data, module breakage is rare, occurring in approximately 1% of modules over the 25 year operating life[95]. Besides, over one-third of these breakages occurs during shipping and installation and are removed before operation. Moreover, a proportion of broken modules have only chipped glass, which does not affect the semiconductor material. According to First Solar's data, field breakages largely consist of various types of stress and impact fractures (caused for example by hail). Stress fractures are caused by dynamic/static loads such as wind, snow, and ice, or by thermal or physical propagation of undetected microscopic defects resulting from installation and handling damage. Also, module breakage can occur at the attachment point due to improper clamping.

First Solar has calculated through fate and transport analysis the potential exposures to Cd for rainwater leaching from broken modules in an industrial rooftop scenario in California and southern Germany (Baden-Württemberg)[95]. The calculations were based on a worst case leaching scenario of total release of Cd, and the calculated exposure point concentrations were compared to residential screening levels. It was concluded that, even in the event of a total release of Cd, the impacts to soil, air, and groundwater were 1 to 5 orders of magnitude below human health screening levels in California and southern Germany exposure scenarios. The estimated exposure point concentration of ground water calculated for California was of 0.8 μg/L, while the regulatory ground-water screening level is 5 μg/L. It was therefore concluded that potential exposures to Cd from rainwater leaching of broken modules in a commercial building scenario were unlikely to pose a potential health risk to on-site workers or off-site residents. Apart from the previous study, First Solar has internally conducted a sensitivity analysis regarding the quantity of semiconductor material potentially susceptible to rainwater leaching in a broken CdTe PV module[94]. In this experiment a total number of 12 modules, representative of 4 breakage categories, were subjected to 12 simulated rainfall events of 5 minutes duration each with a pH of 4.5. As a result, the mean total mass of Cd in leachate from broken modules varied from 0.002% to 0.007% of the total mass of Cd in a module. This experimentally measured mass of Cd in leachate provides an additional margin of safety in the previous calculations, which assumed total (100%) release of Cd content.

Although peer-reviewed fate and transport investigations regarding leaching of broken or defective CdTe PV modules suggest that the potential risk is minimal, independent

[94] P. Sinha, "Assessment of leaching tests for evaluating potential environmental impacts of PV module field breakage," *IEEE Journal of Photovoltaics*, vol. 5, no. 6, pp. 1710-1714, September 2015.
[95] P. Sinha, "Fate and Transport evaluation of potential leaching risks from cadmium telluride photovoltaics," *Environmental Toxicology and Chemistry*, vol. 31, no. 7, pp. 1670-1675, 2012.

investigations, published in peer-reviewed scientific journals would contribute to support First Solar's experimental results. These scientific studies should include both, broken modules representative of field exposures and modules with integrity issues resembling possible situations encountered towards the end of life. For example, independent broken module leaching studies have historically been conducted by Fraunhofer Institute in Germany[96] and NEDO[97] in Japan on older generation CdTe PV modules with results below health and environmental screening limits.

Potential impacts from module breakage are minimized with routine inspections of modules or power output monitoring. For example, the latter may include diagnostic comparison of actual to expected performance or comparison of co-located arrays to identify low performance areas and modules that are nonfunctioning potentially due to breakage. This is done as part of O&M activities, and leads to a prompt detection of integrity issues which reduce any potential risk of Cd exposure to negligible limits.

##### 2.3.4.2.- Non-intended uses, uncontrolled disposal and improper recycling of CdTe PV modules

In this section, the EH&S aspects of First Solar's CdTe PV modules that have received a non-intended use will be analyzed. This analysis is extended to the disposal of end-of-life CdTe PV modules into uncontrolled landfills.

First Solar's CdTe PV modules are primarily used in the utility scale market segment, although the company is also active in commercial and industrial applications. Therefore, the possibility of First Solar's CdTe PV modules being used by non-qualified third persons is limited, assuming that utility scale installations are permanently under supervision including its end of life. Moreover, as long as their physical integrity is maintained, CdTe PV modules do not pose a risk to the environment or to the human safety.

The deployment of photovoltaic technology has experienced in the previous years an outstanding advance and is forecasted to boom worldwide in the next decades. Although the European Union has led this path in the previous years, other countries like China, US, Japan, and India are expected to play a key role in the installation of PV modules in the near future and later other regions will join that activity. As a consequence of this massive deployment, an enormous amount of PV modules will reach their end of life in the subsequent years. According to IRENA and IEA-PVPS[98] by 2030 approximately 8 million tonnes of cumulative PV panels will have been converted in waste and almost 78 million of tonnes by 2050. Assuming a constant market share of 5% for CdTe PV modules, this provides an amount of 400,000 tonnes of cumulative CdTe panels converted in waste by 2030, and almost 4 million of tonnes by 2050. By 2050 the five main producers of PV waste will be China, US, Japan, India, and Germany[98].

[96] H. Steinberger, "Health, Safety and Environmental Risks from the Operation of CdTe and CIS Thin-film Modules," *Progress in Photovoltaics: Research and Applications,* vol. 6, pp. 99-103, 1998.
[97] "Fiscal 1998 Report on the Results of Work Entrusted to the Renewable Energy and Industrial Technology Development Organization," *Central Research Institute for the Electric Power Industry (CRIEPI)*, 1999.
[98] S. Weckend *et al., "*End-of-life management. Solar photovoltaic panels,*" IRENA and IEA-PVPS*, Report number T12-06:2016, 2016.

Despite these anticipated huge PV waste volumes, at this moment, only the European Union has adopted regulations that specifically cover PV waste, which include collection, recovery and recycling objectives. Based on the extended-producer responsibility, the WEEE Directive forces producers to finance the cost of collecting and recycling end-of-life PV panels delivered to the European market. The lack of regulations for the end-of-life collection and recycling of PV modules, with the exception of the European countries, means that PV end-of-life management outside of Europe is subject to general waste regulations and in practice, PV modules could be disposed of rather than recycled.

Worldwide most countries classify PV panels as general or industrial waste, although in countries such as Japan or the US, waste regulations include hazardous waste characterization leaching tests. The limit for leachate Cd concentration is 1 mg/L in the US, 0.3 mg/L in Japan and 0.1 mg/L in Germany, but the leaching tests are also different. According to various leaching experiments it ranges from non-detectable values to 0.91 mg/L for Cd[94,99]. Several authors have studied the leaching behavior of CdTe PV modules in different leaching test conditions such as pH, $O_2$, and test duration[100,101,102]. For example, Zeng *et al.*[101] showed that the release of soluble Cd from the raw material CdTe in the TCLP and WET tests was about 1500 and 260-fold higher, respectively, than the regulatory limit of 1 mg/L. In an additional communication, First Solar pointed out the fact that this study conducted the leaching tests on the raw CdTe material rather than on PV module fragments, which have quantities of CdTe that are lower than the Zeng *et al.* tests by three orders of magnitude and encapsulate CdTe in a monolithic glass-adhesive laminate-glass structure[103]. Nevertheless, the authors indicated that there is a potential for substantial Cd dissolution, even if the initial concentration would be three orders of magnitude lower[104]. The authors highlighted the necessity of further experiments resembling conditions found in municipal solid waste landfills, which has recently been conducted in a landfill in the State of Arizona (US) with leaching test results below the regulatory limit of 1 mg/L[99]. In another study[102], the authors investigated the leaching behavior of milled module pieces of 0.2 mm size, and verified that acidic solutions produce substantial leaching. Based on the landfill experiments conducted in Arizona, milled module pieces of 0.2 mm size are not representative of landfill conditions. When CdTe PV modules were crushed by six passes with a heavy-duty landfill compactor (contact load of 45,000 kg), the glass-adhesive laminate-glass structure was retained and three-quarters of module pieces were greater than 1 cm in size and 99% were greater than 0.1 mm in size. The assumption of long-lived acidic conditions is also not consistent with landfill conditions, which have predominantly neutral to

[99] P. Sinha *et al*., "Evaluation of potential health and environmental impacts from end-of-life disposal of photovoltaics," in *Photovoltaics,* New York, Nova Science Publishers, Inc., pp. 37-51, 2014.
[100] G. Okkenhaug *et al*., "Environmental risks regarding the use and end-of-life disposal of CdTe PV modules," *Norwegian Geotechnical Institute*, Norway, 20092155-00-5-R, 16 April 2010.
[101] C. Zeng, "Cadmium telluride (CdTe) and cadmium selenide (CdSe) leaching behavior and surface chemistry in response to pH and $O_2$," *Journal of Environmental Management*, vol. 154, pp. 78-85, 2015.
[102] R. Zapf-Gottwick, "Leaching hazardous substances out of photovoltaic modules," *International Journal of Advanced Applied Physics Research*, vol. 2, pp. 7-14, 2015.
[103] P. Sinha, "Cadmium telluride leaching behavior: Discussion of Zeng *et al*." *Journal of Environmental Management*, vol. 163, pp. 184-185, 2015.
[104] C. Zeng, "Response to the comments on "Cadmium telluride leaching behavior: Discussion of Zeng *et al*. (2015)"," *Journal of Environmental Management*, vol. 164, pp. 65-66, 2015.

slightly basic (methanogenic) conditions over their lifetime, which render metal ions immobile[99].

In the following table, for the sake of clarity, a summary of the different leaching tests and experiments is shown.

| | Sample (size) | Solvent | Liquid to solid ratio | Test temperature (°C) | Test duration | Leachate Cd concentration | Limit |
|---|---|---|---|---|---|---|---|
| **TCLP-United States. US[105]** | CdTe PV module (1 cm) | Sodium acetate/acetic acid (pH=2.88 for alkaline waste, pH=4.93 for neutral to acidic waste) | 20:1 | 23±2 | 18±2 h | 0.22 mg/L | 1 mg/L |
| **DIN EN 12457-4:01-03Germany[106]** | CdTe PV module (1 cm) | Distilled water | 10:1 | 20 | 24 h | (0.0016-0.0040) mg/L | 0.1 mg/L |
| **Notice 13/JIS K 0102:2013 method (JLT-13)-Japan[107]** | CdTe PV module (0.5 cm) | Distilled water | 10:1 | 20 | 6 h | (0.10-0.13) mg/L | 0.3 mg/L |
| **Zeng *et al*. (TCLP and WET) (2015)** | CdTe raw material (99.999 %) (63-125) microns | TCLP: Acetic acid, sodium hydroxide (pH=4.93) | 20:1 | Room | 18 h | 1490.9 mg/L | 1 mg/L |
| | CdTe raw material (99.999 %) (63-125) microns | WET: Citric acid, sodium hydroxide (pH=5.00) | 10:1 | Room | 48 h | 260.5 mg/L | 1 mg/L |
| **Okkenhaug *et al*. (EN 12457) (2010)** | CdTe PV module (<0.4 cm) | Deionized water | 10:1 | 20±5 | 24 h | 0.73 mg/kg dw | 1 mg/kg dw (ordinary waste landfill) |
| **Zapf-Gottwick *et al*. (2015)** | CdTe PV module (0.02 cm) | Low mineralized water pH=8.4 | 20:1 | Room | 56 days | <5% | - |
| | | Seawater pH=7.8 | | | | <1% | - |
| | | Rainwater pH=3 | | | | ~50% | - |

**Table 6** Summary of different leaching tests and experiments.

Fate and transport analysis is required to understand how leachate will migrate from the emission point to the exposure point in order to evaluate the consequences for the environment

[105] J. Bousselaire, "Analytical Report: Metals-TCLP," Test America, Irvine, CA, 2013.
[106] BAM Federal Institute for Materials Research and Testing, Test Report, Berlin, Germany, 2005.
[107] Ministry of Environment and Ministry of Economy Trade and Industry, "Reuse, recycle and proper disposal of spent renewable energy equipment," Japan, 2014.

and human health. This fate and transport analysis of Cd in the environment following CdTe panel disposal into uncontrolled landfill has been studied by several authors[108,99] by means of the Hazardous Waste Delisting Risk Assessment Software (DRAS) provided by the US Environmental Protection Agency (EPA). In this regard, Cyrs *et al.*[108] conducted a comprehensive investigation regarding the volume of CdTe modules that could be disposed in a single landfill over 20 years. Cadmium TCLP concentration is a key input parameter in the DRAS simulations, since it directly impacts the calculated risks. In this investigation they used Cd TCLP concentrations of 1.0 mg/L and 0.5 mg/L that represent the maximum current and anticipated TCLP concentration. It is important to point out that DRAS is based on several assumptions that yield conservatively high estimates of potential risk, such as landfills not lined, no control for surface water runoff, and continuous Cd leaching until no Cd remains in the PV modules. According to their results, the screening level cumulative non-carcinogenic hazard index could exceed 1.0[109] only if the annual waste volume amounted to 354,000 modules or more with a TCLP value of 1.0 mg/L (cumulative volume of over 7 million modules over 20 years), or to 708,000 modules or more with a TCLP value of 0.5 mg/L (cumulative volume of over 14 million modules over 20 years). The latter estimate is more representative of First Solar modules which have TCLP values ranging from (0.19-0.22) mg/L[94,99]. In the context of non-carcinogenic health risk, the results from Cyrs *et al*. showed that the exposure associated with ground water contamination is of more concern than an exposure associated with surface pathways.

On the other hand Sinha *et al.*[99] also used the DRAS model to evaluate the potential health and environmental impacts associated with the disposal of a 25 MW utility scale installation (approximately 250,000 CdTe PV modules) in an unlined landfill during one year. Besides, they studied the influence of increases in pH that typically take place in landfills over time in the calculated health risks. In the context of this work, five CdTe First Solar PV modules were crushed with a compactor, in order to experimentally evaluate the representativeness of the TCLP leachate data. A representative sample was selected from each module and sent for TCLP and STLC tests. The analyzed Cd concentration in the leachate ranged from <0.1 mg/L to 0.19 mg/L for the TCLP test and 0.57 mg/L to 0.91 mg/L for the STLC test (US regulatory limit for non-hazardous waste is 1 mg/L). They obtained a total hazard quotient of 0.045 and 0.001 for acidic and basic landfill conditions, respectively, well below the human screening limit set at 1.0 (margin of safety of over 20). Therefore, according to the results provided in this investigation, the one-time disposal of 250,000 CdTe PV modules (or over 5 million modules considering the margin of safety, which would equal the disposal of an installation well above 500 MW peak performance in 1 year) is not likely to represent a significant cancer risk or non-cancer hazard, for both the acidic and basic scenarios in unlined landfills. The disposal of a multi 100 MW PV installation in a single uncontrolled landfill is already an upper bound case.

[108] W. D. Cyrs *et al*., "Landfill waste and recycling: Use of a screening-level risk assessment tool for end-of-life cadmium telluride (CdTe) thin-film photovoltaic (PV) panels," *Energy Policy*, vol. 68, pp. 524-533, 2014.
[109] A hazard index below 1.0 indicates that the cadmium concentration in each exposure pathway is below the safe dose, suggesting no increase in health risk.

Although the disposal of CdTe PV modules in uncontrolled landfills does not seem to pose a significant environmental and health risk, proper recycling is the ideal option for all end of life PV modules. The recycling option provides important benefits, such as the recovery of valuable materials, the generation of new industrial opportunities and the avoided generation of uncontrolled waste, which contribute towards a sustainable energy production. First Solar has demonstrated a commitment to providing recycling solutions to the modules reaching their end of life. First Solar started its global recycling program in 2005 which was available to its customers through a prefunded program. At the end of 2012, this prefunded program was replaced by a new program whereby customers were offered recycling services via a separate contract (RSA or Recycling Service Agreement). Currently, First Solar continues to provide recycling services, operate recycling facilities, and invest in recycling technology. In future, First Solar may broaden recycling technology to include also recycling of crystalline silicon modules. Nevertheless, since high-value recycling (recovery of glass and semiconductor material) of CdTe PV modules involves handling Cd and its compounds, it must be entrusted to reliable companies with the required knowledge and best environmental, health, and safety practices, such as those being documented by CENELEC in support of the WEEE Directive (draft Standard EN50625-2-4[110]). In the case of informal recycling, unlike household consumer electronics and other products, there are few components in a monolithic thin film module valuable for being dismantled, aside from the junction box and cables, and the above analysis of uncontrolled landfills applies in case of uncontrolled disposal.

### 2.3.5.- END-OF-LIFE DISPOSAL AND POLICIES

It is well accepted by the PV community that recycling is the most sustainable manner to handle PV modules at the end of their useful life. The socio-economic benefits encompass aspects such as avoidance of potential environmental impact, improvement in resources efficiency and a new business opportunity in waste management[111].

First Solar is committed to a responsible product life cycle and end-of-life management. Recyclability is fully integrated into all new products developments and budget is allocated for recycling process upgrades. All First Solar production plants have an operational recycling facility and the company continuously works on improvements in technology, processes and cost reduction. The technology improvements implemented have resulted in an overall cost reduction of over 50%[112] (see Figure 34). First Solar’s policy of encouraging sustainable recycling by driving costs down is based on the thought that increased volumes of PV modules at end-of-life and improved experience in recycling, accompanied by rising disposal costs, will become the main factors that lead to recycling being more commercially attractive than disposal.

[110] https://standardsdevelopment.bsigroup.com/Home/Project/201602172
[111] IRENA and IEA-PVPS, “End-of-life Management: Solar Photovoltaic Panels”, International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems, 2016.
[112] First Solar private communication, June 2016.

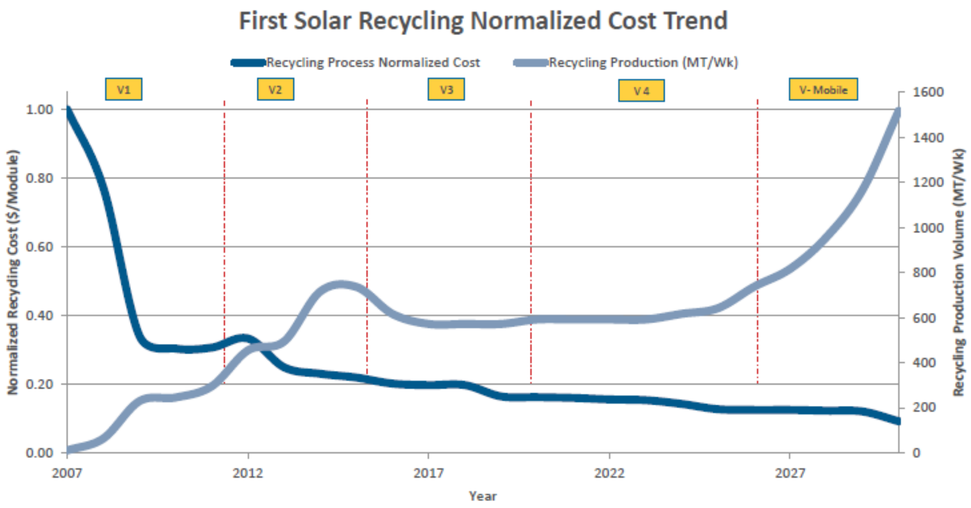



**Figure 34** First Solar's recycling normalized cost trend[113].

In 2005, First Solar established the first global module recycling program in the PV industry using a pre-funded approach, and since then, they are leaders in PV recycling programs in the industry. At the end of 2012, First Solar discontinued the pre-fund program in all markets except the EU[114].

In 2013, First Solar issued a document with the key lesson learned extracted from the EU experience in PV module recycling[115]. This same year, the Company launched a new program denominated "Recycling Service Agreement" (RSA). In this new approach, First Solar offers to customers a separate cost-effective contract at a price guaranteed for two years which commits the customer to recycling PV modules. After this period, First Solar offers new contracts, in two years blocks, that can benefit from any price decreases. This approach is based on a "pay-as-you-go" model that is globally available, scalable from construction to decommissioning, can be easily integrated into Operation and Maintenance activities, EPCs and PV power plants activities and most likely, will benefit customers due to the projected recycling cost reduction[116]. First Solar's RSA contract does not obligate customers to use the Company's recycling services. Module owners have the discretion to elect alternate recycling vendors or opt for responsible disposal.

It is worth noting that, in the future, First Solar may broaden recycling activities to include c-Si technology as they aim, on the one hand, to continue leading the recycling industry and, on the other hand, to offer a more attractive RSA pricing to their customers as they foresee an increase of end-of-life PV module volumes.

In the EU, PV modules are included in the Waste Electrical and Electronic Equipment

[113] L. Kraemer, "FS technology Safety and Sustainability Benefits", Perrysburg site visit, June 2016
[114] R. Subramanian, "First Solar: The solar Module Recycling Opportunity", Ivey Publishing, 2016.
[115] First Solar, "End-of-Life management of photovoltaic modules", 2013.
[116] S. Raju, "First Solar's Industry Leading PV Thechnology and Recycling Program", *Solar Power International*, Chicago (Illinois), 2013.

(WEEE)[117] directive that came into effect in all Member States on February 2014. The directive extended the producer's responsibility to include collection and recycling for all PV technologies free of charge to the end-user. To that end, First Solar fulfills all the obligations established under the WEEE directive for their products including specific mark symbol and financial aspects. Furthermore, in the EU, First Solar is focused on the utility-scale segment via business-to-business channels and their products are not available to end-users and residential applications[118].

First Solar is leading the PV industry with the establishment of collection and recycling programs that ensure end-of-life recycling using a proven technology. In the EU, the inclusion of all PV technologies in the WEEE directive and First Solar's recycling facility (in Frankfurt/Oder, Germany) ensures the responsible management of CdTe PV technology at end of life.

Outside of the EU, First Solar's recycling services are globally available and implemented with recycling facilities in Perrysburg, USA and Kulim, Malaysia. First Solar is developing a future recycling version that is planned to be mobile[119]. Outside the EU, the adoption by owners to choose recycling over disposal is based on competitive pricing.

## 2.4.- LIFE CYCLE IMPACTS OF THE LARGE-SCALE DEPLOYMENT OF THE CdTe TECHNOLOGY AND COMPARISON WITH OTHER TECHNOLOGIES

In this chapter, a discussion is presented of the available information on the energy and environmental impacts associated to CdTe PV systems, from the point of view of their whole life cycle performance.

### 2.4.1.- CUMULATIVE ENERGY DEMAND, ENERGY RETURN ON INVESTMENT, ENERGY PAY-BACK TIME AND GREENHOUSE GAS EMISSIONS

When describing a PV system's life cycle, the following definitions may be employed:

- $\mathbf{t_c}$ = duration of the PV system's manufacturing and installation phase;
- $\mathbf{t_L}$ = duration of the PV system's use phase;
- $\mathbf{t_d}$ = duration of the PV system's decommissioning phase;
- **T** **=** $\mathbf{t_c} + \mathbf{t_L} + \mathbf{t_d}$ = total PV system lifetime;
- $\mathbf{Inv_c}$ = commercial energy investment for PV system manufacturing and installation

[117] European Parliament and the Council of the European Union, Directive2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast), Offic. J. Europ.,Union 197 38–71, 2012.
[118] EPPA, "Socio-economic analysis of the inclusion of solar panels in the scope of the RoHS directive", 2016.
[119] S. Raju, 2013. "First Solar's Industry Leading PV Technology and Recycling Program". *Solar Power International*, Chicago, Illinois, USA, 2013

(including BOS[120]), expressed in terms of the corresponding cumulative demand for primary energy;

- **$Inv_{op}$** = commercial energy investment for PV system maintenance and operation, expressed in terms of the corresponding cumulative demand for primary energy;
- **$Inv_d$** = commercial energy investment for PV system decommissioning[121], expressed in terms of the corresponding cumulative demand for primary energy;
- **Inv** = **$Inv_c$** + **$Inv_{op}$** + **$Inv_d$** = total commercial energy investment over PV system lifetime;
- **PE** = total freely-available primary energy captured in the form of solar irradiance during the PV system's use phase;
- **Out** = total electricity produced by the PV system during its use phase;
- $\eta_G$ = average life-cycle conversion efficiency of the electricity grid of the region in which the PV system is installed;
- **$Out_{PE\text{-}eq}$** = **($Out / \eta_G$)** = total electricity produced by the PV system during its use phase, expressed in terms of *equivalent* primary energy, where such equivalency is calculated on the basis of $\eta_G$.

As shown in Figure 35, during the system's use phase, electricity production (**Out**) is driven by the photochemical conversion of freely-available primary energy (**PE**), and there is only a negligible demand for commercial energy inputs (**$Inv_{op}$**). Use-phase emissions (in the form of carbon dioxide and other gases) are correspondingly very low, since they are only due to this very limited demand for commercial energy carriers.

However, when considering the full life cycle of the PV system, larger investments of commercial energy (**$Inv_c$** and **$Inv_d$**), and correspondingly larger emission flows, are to be accounted for.

[120] The Balance Of System (BOS) of a PV system comprises both a mechanical support structure, and a number of auxiliary electrical components such as cabling, inverters, etc.
[121] As will be discussed later in section 2.4.6.-, the (partial) recycling of the PV system materials at end of life may afford significant energy and emission 'credits', resulting in reduced CED and EPBT and correspondingly increased EROI.

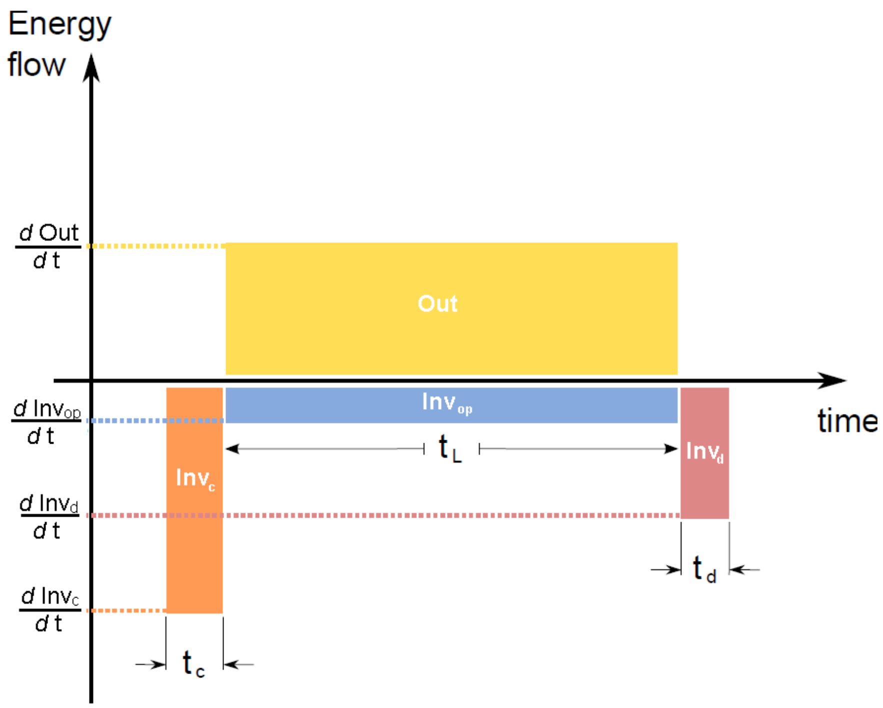



**Figure 35** Schematic depiction of the energy 'investments' (**$Inv_c$** + **$Inv_{op}$** + **$Inv_d$**) and of the energy 'return' (**Out**) of a PV system. The individual areas are drawn for illustrative purposes only, and are not intended to be quantitatively representative of a typical CdTe PV system.
Source: Raugei *et al.*[122]., adapted from Herendeen[123].

The following key energy indicators may thus be calculated:

- **Cumulative Energy Demand per unit of electricity output**

  **CED = (PE + Inv) / Out**

  This is the total primary energy harvested from the environment over the full life cycle of the PV system in order to produce one unit of electricity. In practice, the captured solar energy (**PE**) is always equal to 1 $MJ/MJ_{el}$, or 3.6 $MJ/kWh_{el}$, and hence it is straightforward to calculate **CED** from **Inv**, and *vice versa*.

- **Energy Return on Investment**

  **$EROI_{el}$ = Out / Inv**

  This is the ratio of the total electricity produced by the PV system during its use phase to the sum of all the commercial energy investments for PV system manufacturing, installation, maintenance, operation and decommissioning (where all investments are expressed in terms of the corresponding cumulative demand for primary energy).

- **Energy Return on Investment in terms of equivalent primary energy**

  **$EROI_{PE\text{-}eq} = Out_{PE\text{-}eq} / Inv = EROI_{el} / \eta_G$**

[122] M. Raugei *et al.*, "Methodological guidelines on Net Energy Analysis of Photovoltaic Electricity," IEA-PVPS Task 12, Report T12-07:2016. Available on line at http://www.iea-pvps.org

[123] R. Herendeen, "Net energy analysis: concepts and methods," *Encyclopedia of Energy,* Cleveland C.J. Elsevier, 2004, pp. 283–289.

This is a similar indicator to $EROI_{el}$, but where the total electricity produced by the PV system during its use phase is expressed in terms of *equivalent* primary energy (such equivalency being calculated on the basis of the average life-cycle conversion efficiency of the electricity grid of the region in which the PV system is installed).

The fundamental rationale for **$EROI_{PE-eq}$** is that, in order for an energy production system to provide a positive net energy 'gain' (**NEG**) to the end user, the gross energy output of the system must be larger than the total energy 'investment' required over its lifetime, when both quantities are consistently expressed in units of primary energy. In other words, the following condition must be met[124,125]:

$$\mathbf{NEG} = (\mathbf{Out_{PE\text{-}eq}} - \mathbf{Inv}) > 0 \;\Leftrightarrow\; \mathbf{EROI_{PE\text{-}eq}} > 1$$

- **Energy Pay-Back Time**

  $$\mathbf{EPBT} = \mathbf{Inv} / (\mathbf{Out_{PE\text{-}eq}} / \mathbf{T}) = \mathbf{T} / \mathbf{EROI_{PE\text{-}eq}}$$

  This indicator expresses how long it takes for the PV system to produce an amount of electricity that is *equivalent* to the sum of all the commercial energy investments for PV system manufacturing, installation, maintenance, operation and decommissioning (such equivalency being calculated on the basis of the average life-cycle conversion efficiency of the electricity grid of the region in which the PV system is installed).

Table 7 summarizes the available values for Energy Investment (**Inv**), Energy Return On Investment (**$EROI_{PE-eq}$**), Energy Pay-Back Time (**EPBT**) and Global Warming Potential (**GWP**) of CdTe PV systems as they have been published in the scientific literature over the last decade, in chronological order.

Studies that only collated previously published results[126,127,128,129], rather than produced new estimates, have not been included in this summary.

Wherever possible, those indicators that were not explicitly reported in the surveyed studies have been inferred or back-calculated on the basis of the other available data and parameters.

[124] M. Raugei and E. Leccisi, "A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom," *Energy Policy,* vol. 90, pp. 46-59, 2016.
[125] V. Fthenakis and M. Raugei, "*Life cycle assessment of photovoltaics*," in: The Performance of Photovoltaic Systems: Modelling, measurement and assessment N. Pearsall, (Ed.), Elsevier, in press.
[126] M. Bravi *et al.*, "Life cycle assessment of advanced technologies for photovoltaic panels production," *Int. J. Heat & Technol.*, vol. 28, no.1, pp. 133-140, 2010.
[127] R. Laleman *et al*., "Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation," *Ren Sust En Rev*, vol. 15, pp. 267-81, 2011.
[128] H. C. Kim and V. Fthenakis, "Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation Systematic Review and Harmonization," *J Ind Ecol*, vol. 16, no. S1, pp. S110-S121, 2012.
[129] K. P. Bhandari *et al.*, "Energy paybacktime (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis," *Ren Sust En Rev.*, vol. 47, pp. 133-141, 2015.

| Ref. | Inst. Type | η | Irr [kWh / ($m^2$·yr)] | T [yr] | PR | Inv [MJ / $kWh_{el}$] | $EROI_{PE-eq}$ [MJ/MJ] | EPBT [yr] | GWP [$gCO_2$-eq / $kWh_{el}$] |
|---|---|---|---|---|---|---|---|---|---|
| Jungbluth *et al.*[130a] | R | 7.1% | 1,117 | 30 | 75% | 1.02 | 11 | 2.7 | - |
| Raugei *et al.*[131a] | R | 9.0% | 1,700 | 20 | 75% | 0.86 | 13 | 1.5 | 48 |
| Fthenakis *et al.*[132] | G | 9.0% | 1,800 | 30 | 80% | - | - | - | 24 |
| Ito *et al.*[133] | G | 9.0% | 2,017 | 30 | 77% | - | - | - | 47 |
| Fthenakis *et al.*[134] | G | 10.9% | 1,700 | 30 | 80% | 0.34 | 38 | 0.8 | 20 |
| Dominguez-Ramos *et al.*[135] | G | 9.0% | 1,825 | 30 | 78% | - | - | - | 17 |
| Ito *et al.*[136] | G | - | 1,702 | - | 78% | 0.77 | 16 | 2.2 | 51 |
| Held and Ilg[137b] | G | 10.9% | 1,700[c] | 30 | 80% | 0.29 | 38 | 0.8 | 19 |
| Raugei *et al.*[138] | G | 10.9% | 1,700 | 30 | 80% | 0.31 | 38 | 0.8 | - |
| Kim *et al.*[139] | G | 11.2% | 1,810 | 30 | 80% | 0.18 | 43 | 0.7 | 11 |
| Seitz *et al.*[140] | R | 13.1% | - | - | - | - | - | - | 20 |
| De Wild-Scholten[141], (EU) | R | 11.9% | 1,700 | 30 | 75%[d] | 0.21 | 44 | 0.7 | 16 |
| DeWild-Scholten[141],(CN) | R | 11.9% | 1,700 | 30 | 75%[d] | 0.21 | 44 | 0.7 | 20 |
| Bergesen *et al.*[142] | G | 11.6% | 1,800 | 30 | 80% | - | - | - | 20 |
| Marini *et al.*[143] | G | 11.7% | 1,800 | 30 | 80% | - | - | - | 18 |

[130] N. Jungbluth *et al.*, "Life Cycle Assessment of Photovoltaics; Update of the ecoinvent Database," *MRS Online Proceedings Library*, 2007.
[131] M. Raugei *et al.*, "Life Cycle Assessment and Energy Pay-Back Time of Advanced Photovoltaic Modules: CdTe and CIS compared to poly-Si," *Energy,* vol. 32, no. 8, pp.1310-1318, 2007.
[132] V. M. Fthenakis *et al.*, "Emissions from photovoltaic life cycles," *Environ. Sci. Technol.* Vol. 42, pp. 2168–2174, 2008.
[133] M. Ito *et al.*, "A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules," *Prog. Photovolt: Res. Appl.* vol. 16, no. 1, pp. 17–30, 2008.
[134] V. Fthenakis *et al.*, "Update of PV energy payback times and life-cycle greenhouse gas emissions, "*24th European Photovoltaic Solar Energy Conference and Exhibition (EU-PVSEC)*, Hamburg, Germany, 2009.
[135] A. Dominguez-Ramos *et al.*, "Prospective CO2 emissions from energy supplying systems: Photovoltaic systems and conventional grid within Spanish frame conditions," *Int J of Life Cycle Assess,* vol. 15, no. 6, pp. 557–566, 2010.
[136] M. Ito *et al.*, "Life-cycle analyses of very-large scale PV systems using six types of PV modules," *Current Applied Physics* vol. 10, pp. S271–S273, 2010.
[137] M. Held and R. Ilg, "Update of environmental indicators and energy payback time of CdTe PV systems in Europe," *Prog. Photovolt: Res. Appl.* vol. 19, pp. 614–626, 2011.
[138] M. Raugei *et al.*, "The Energy Return on Energy Investment (EROI) of Photovoltaics: Methodology and Comparisons with Fossil Fuel Life Cycles," *Energy Policy,* vol.45, pp.576-582, 2012.
[139] H. Kim *et al.*, "Life Cycle Assessment of CdTe Photovoltaic System," in *Design for Innovative Value Towards a Sustainable Society* , Springer Netherlands, Online ISBN 978-94-007-3010-6, 2012 pp. 1018-1020.
[140] M. Seitz *et al.*, "Eco-efficiency Analysis of Photovoltaic Modules," Bifa Environmental Institute, 2013.
[141] M. de Wild-Scholten, "Energy payback time and carbon footprint of commercial photovoltaic systems," *Solar En Mat Solar Cells,* vol. 119, pp. 96–305, 2013.
[142] J. D. Bergesen *et al.* "Thin-Film Photovoltaic Power Generation Offers Decreasing Greenhouse Gas Emissions and Increasing Environmental Cobenefits in the Long Term," *Env. Sci. Tech*. vol. 48, no. 16, pp. 9834-9843, 2014.
[143] C. Marini *et al.*, "A Prospective Mapping of Environmental Impacts of Large Scale Photovoltaic Ground Mounted Systems Based on the CdTe Technology at 2050 Time Horizon," *29th European Photovoltaic Solar Energy Conference and Exhibition (EU-PVSEC)*, Amsterdam, The Netherlands, 2014.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Hertwich *et al.*[144] [b]** | G | 11.6% | 1,700 | 30 | 80% | - | - | - | 16 |
| **Hertwich *et al.*[144]** | R | 11.6% | 1,700 | 30 | 75% | - | - | - | 21 |
| **Wyss *et al.*, 2015[145][b]** | G | 14.0% | 1,331 | 30 | 73% | 0.48 | - | - | 30 |
| **Wyss *et al.*, 2015[145][b]** | R | 14.0% | 1,331 | 30 | 73% | 0.38 | - | - | 25 |
| **Raugei and Leccisi[124]** | G | 13.4% | 1,000 | 30 | 80%[d] | 0.37 | 25 | 1.2 | - |
| **Leccisi *et al.*[146] (US)** | G | 15.6% | 1,700[c] | 30 | 80% | 0.26 | 46 | 0.7 | 16 |
| **Leccisi *et al.*[146](MY)** | G | 15.6% | 1,700[c] | 30 | 80% | 0.24 | 50 | 0.6 | 15 |

**Table 7** Energy Investment (**Inv**), Energy Return On Investment (**EROI$_{PE\text{-}eq}$**), Energy Pay-Back Time (**EPBT**) and Global Warming Potential (**GWP**) of CdTe PV systems; values as published.
**R** = rooftop; **G** = ground-mounted; η = module efficiency; **Irr** = solar irradiation; **T** = lifetime; **PR** = performance ratio. (US) = assuming production in the USA; (MY) = assuming production in Malaysia.

[a] These results refer to pilot production modules.
[b] These results include end-of-life decommissioning (but no 'credits' for recovered materials).
[c] Other irradiation levels were also considered in this study.
[d] This PR value does not include degradation (which is, however, still accounted for in the results).

When reviewing and comparing the energy and environmental impact indicator values reported in the literature, it is important to keep in mind that these depend on a number of key parameters, as discussed in the guidelines on the Life Cycle Assessment (LCA)[147] and Net Energy Analysis (NEA)[122] of PV systems issued by Task 12 of the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS).

Among such parameters, the following are of foremost importance:

1- Type of installation (rooftop or ground-mounted);
2- Boundary of the analysis (including or excluding end-of-life (EoL) decommissioning, and any 'credits' due to material recovery);
3- Lifetime (**T**);
4- Performance Ratio[148] (**PR**);
5- Irradiation (**Irr**);
6- Life-cycle conversion efficiency of the electricity grid ($\eta_G$).

While items 1 and 2 are intrinsic to each specific analysis, parameters 3 and 4 are always either

[144] E. G. Hertwich *et al.,* "Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies," *PNAS* 112(20), 6277-6282, 2014.
[145] F. Wyss *et al.,* PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots, v.1.4, Switzerland, 2015.
[146] E. Leccisi *et al*., "The energy and environmental performance of ground-mounted photovoltaic systems – a timely update," *Energies,* vol. 9, no. 8, pp. 622, 2016.
[147] R. Frischknecht *et al*., "Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity," 3rd edition. International Energy Agency (IEA) PVPS Task 12, Report T12-08:2016, 2016.Available on line at http://www.iea-pvps.org
[148] The performance ratio (**PR**) describes the difference between the modules' (DC) rated performance (the product of irradiation and module efficiency) and the actual (AC) electricity generation (IEC 61724). System degradation is often included in the PR value too.

estimated or assumed, and parameters 5 and 6 depend not on the PV system per se, but on the geographical area where it is assumed to be installed and on the corresponding electricity grid mix into which it is embedded (and which it is hence assumed to displace). Therefore, as argued multiple times elsewhere[128,129,144] a more meaningful comparison of the energy and environmental performance information available in the literature may be arrived at by harmonizing the results using the same assumptions.

Considering item 1, Table 8 then presents the values for **Inv**, **$EROI_{PE\text{-}eq}$**, **EPBT** and **GWP** of only ground-mounted CdTe PV systems, which are more representative of the majority of First Solar installations to date. Incidentally, however, it is noted that rooftop installations tend to be characterized by lower energy investments, and correspondingly reduced GWP, than ground-mounted systems due to reduced BOS requirements.

Also, with regard to item 2, since most of the surveyed studies did not include the end-of-life (EoL) treatment of the PV systems (nor the potential energy and emission ‘credits’ resulting from the recycling of the recovered materials), for the sake of consistency and harmonization, all the values reported in Table 8 refer to the life cycle of the PV systems *excluding* EoL (the latter will be discussed separately in section 2.4.6.-).

Finally, all the underlying assumptions for parameters 3 – 6 have been harmonized according to the corresponding values recommended by the IEA PVPS Task 12, i.e., respectively:

- Lifetime (**T**) = **30** years;
- Performance Ratio (**PR**) = **0.80**;
- Irradiation (**Irr**) = **1,700** kWh/($m^2$·yr), which is representative of Central-Southern Europe;
- Life-cycle conversion efficiency of the electricity grid (**$\eta_G$**) = **0.31**, which is the correct value for the European Network for Transmission System Operators for Electricity (ENTSOE)[149].

Wherever possible, those indicators that were not explicitly reported in the surveyed studies have been inferred or back-calculated on the basis of the other available data and parameters. However, one of the surveyed studies[140] did not disclose a sufficient number of parameters and assumptions with the necessary transparency, and as a result its results have not been included in Table 8. Also, two studies[133,136] have been excluded from the harmonization because they refer to very large scale (VLS) installations and include a number of additional components such as long-distance transmission lines, etc.

[149] Formerly known as Union for the Coordination of the Transmission of Electricity (UCTE).

| Ref. | η | Inv [MJ / $kWh_{el}$] | $EROI_{PE-eq}$ [MJ/MJ] | EPBT [yr] | GWP [$gCO_2$-eq / $kWh_{el}$] |
|---|---|---|---|---|---|
| **Fthenakis *et al.*** [132] | 9.0% | - | - | - | 25 |
| **Dominguez-Ramos *et al.*[135], 2010** | 9.0% | - | - | - | 18 |
| **Fthenakis *et al.*[134]** | 10.9% | 0.34 | 34 | 0.9 | 20 |
| **Held and Ilg[137]** | 10.9% | 0.27 | 43 | 0.7 | 18 |
| **Raugei *et al.*[138]** | 10.9% | 0.31 | 38 | 0.8 | - |
| **Kim *et al.*[139]** | 11.2% | 0.20 | 59 | 0.5 | 12 |
| **Bergesen *et al.*[142]** | 11.6% | - | - | - | 21 |
| **Marini *et al.*[143]** | 11.7% | - | - | - | 19 |
| **Raugei and Leccisi[124]** | 13.4% | 0.22 | 53 | 0.6 | - |
| **Wyss *et al.*[145]** | 14.0% | 0.33 | 35 | 0.8 | 20 |
| **Leccisi *et al.*[146] (US)** | 15.6% | 0.26 | 44 | 0.7 | 16 |
| **Leccisi *et al.*[146] (MY)** | 15.6% | 0.24 | 48 | 0.6 | 15 |

**Table 8** Energy Investment (**Inv**), Energy Return On Investment (**$EROI_{PE-eq}$**), Energy Pay-Back Time (**EPBT**) and Global Warming Potential (**GWP**) of ground-mounted CdTe PV systems; η = module efficiency; all values harmonized to **T = 30** yr, **PR = 0.8**, **Irr = 1,700** kWh/($m^2$·yr) and **$\eta_G$ = 0.31**. (US) = assuming production in the USA; (MY) = assuming production in Malaysia.

The harmonized literature results attest to the fact that the progressive increase in CdTe PV module efficiency (η) over the approximately ten years since their introduction to the market has been paralleled by a correspondingly steady improvement in terms of energy and carbon emission performance. Such improvements, which are due not only to the increase in module efficiency alone, but also to a concomitant reduction in manufacturing energy, are highlighted in Figure 36 and Figure 37, in which, respectively, the harmonized **EPBT** and **GWP** values (along the vertical axis) are plotted *vs.* the corresponding module efficiencies (along the horizontal axis).

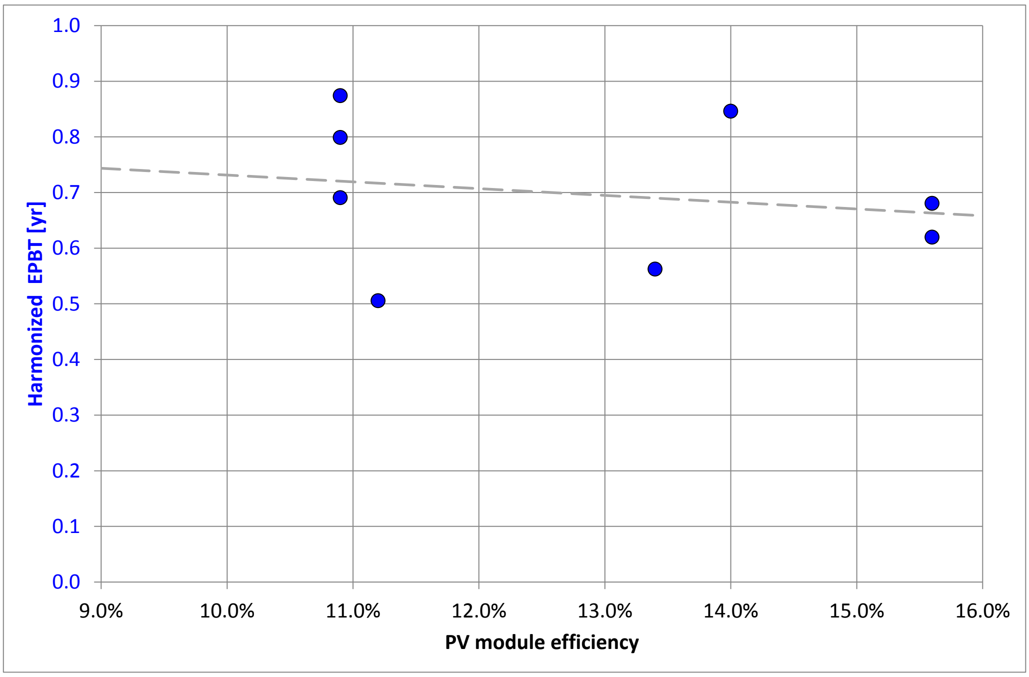



**Figure 36** Energy Pay-Back Time (**EPBT**) of ground-mounted CdTe PV systems, *vs.* increasing PV module efficiency; all values harmonized to **T = 30** yr, **PR = 0.8**, **Irr = 1,700** kWh/($m^2$·yr) and **$\eta_G$ = 0.31** (data from Table 8).

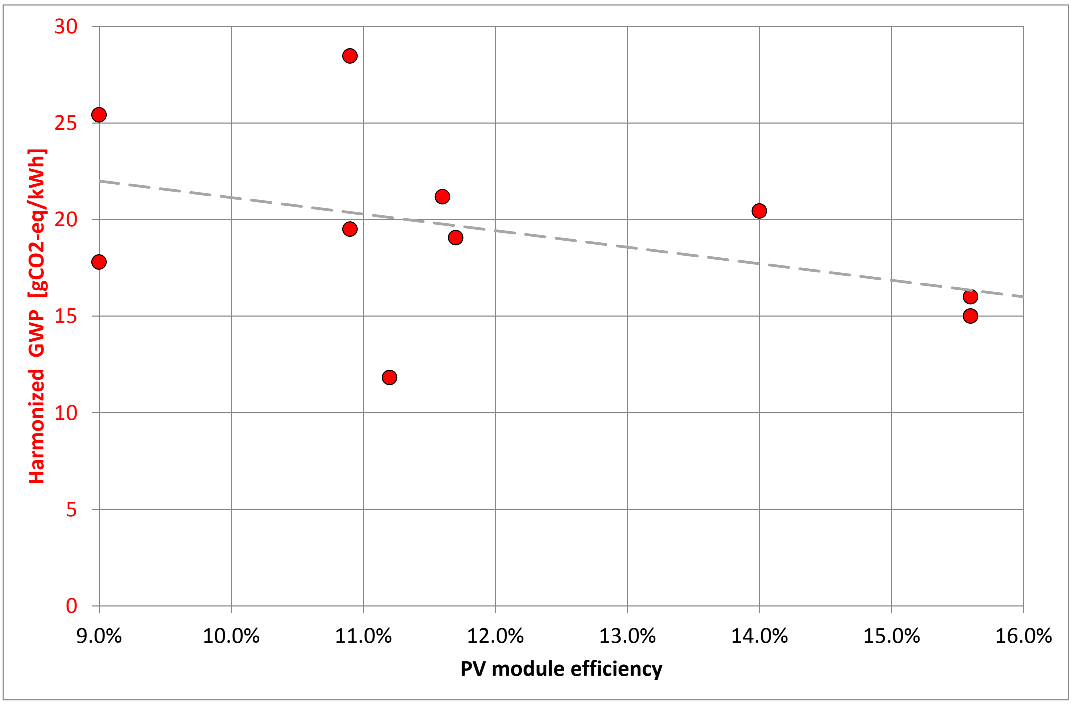



**Figure 37** Global Warming Potential (**GWP**) for ground-mounted CdTe PV systems, *vs.* increasing PV module efficiency; all values harmonized to **T = 30** yr, **PR = 0.8**, **Irr = 1,700** kWh/($m^2$·yr) and **$\eta_G$ = 0.31** (data from Table 8).

It is then of particular interest to discuss in more detail the latest published results that apply to the current generation modules[146].

Firstly, it is interesting to regard the performance of current-generation CdTe PV systems under three different irradiation levels, which broadly span the range between the minimum and maximum levels that are typically encountered in European sites deemed suitable for PV installations. Even in comparatively low-irradiation conditions, such as would be typical of the UK, for instance, ground-mounted CdTe PV systems still maintain an impressively short EPBT of around 1 year, and life-cycle GHG emission levels lower than 30 g($CO_2$-eq) per kWh of electricity produced. At the other end of the scale, when installed in the most favourable conditions, such as e.g. in Southern Spain or in Greece, the EPBT drops to six months, with corresponding extremely low life-cycle GHG emissions of approximately 10 g($CO_2$-eq) per kWh of electricity produced.

Secondly, and no less importantly, these results confirm that, both from the points of view of energy demand and carbon emissions, current CdTe PV is in a leading position amongst the range of commercial PV technologies. In particular, its performance is at least twice as good as that of the most common PV technology, i.e. multi-crystalline Si (mc-Si), and even better when compared to single-crystalline Si (sc-Si) (Figure 38).

| Irradiation | sc-Si PV | mc-Si PV | CdTe PV | CIGS PV |
|---|---|---|---|---|
| 1,000 kWh/(m²·yr) | 2.8 | 2.1 | 1.1 | 1.9 |
| 1,700 kWh/(m²·yr) | 1.6 | 1.2 | 0.6 | 1.1 |
| 2,300 kWh/(m²·yr) | 1.2 | 0.9 | 0.5 | 0.8 |

**Table 9** Energy Pay-Back Time (**EPBT**) of ground-mounted PV systems under three different irradiation levels[146].

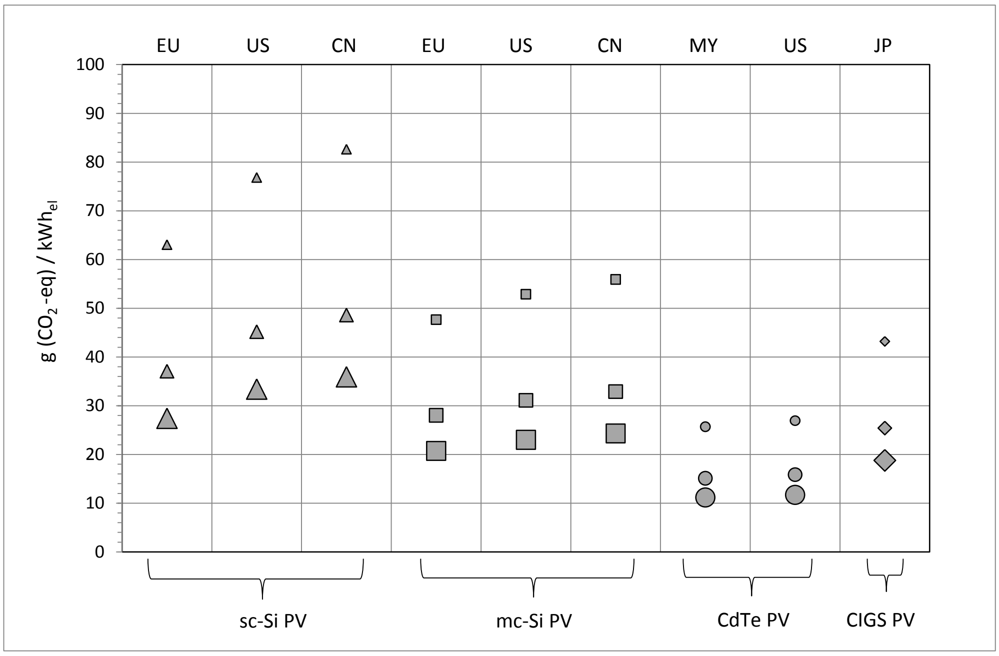



**Figure 38** Global Warming Potential (**GWP**) of ground-mounted PV systems under three different irradiation levels[146].
Small symbols: 1,000 kWh/(m²·yr); medium symbols: 1,700 kWh/(m²·yr); large symbols: 2,300 kWh/(m²·yr).
EU= European Union; US= United States of America; CN= China; MY= Malaysia; JP= Japan.

Last but not least, it is of course of the utmost importance to provide a frame of reference whereby these results may be interpreted in the light of the performance of alternative – and often competing – electricity production technologies. While a full review of all published results for all technologies is clearly beyond the scope of this report, it is nonetheless interesting to contrast the GWP results for CdTe PV presented in Figure 37 and Figure 38 to those from three recent harmonization studies of the life-cycle carbon emissions of three key electricity production technologies, namely coal[150] (Figure 39), nuclear[151] (Figure 40) and wind[152] (Figure 41).

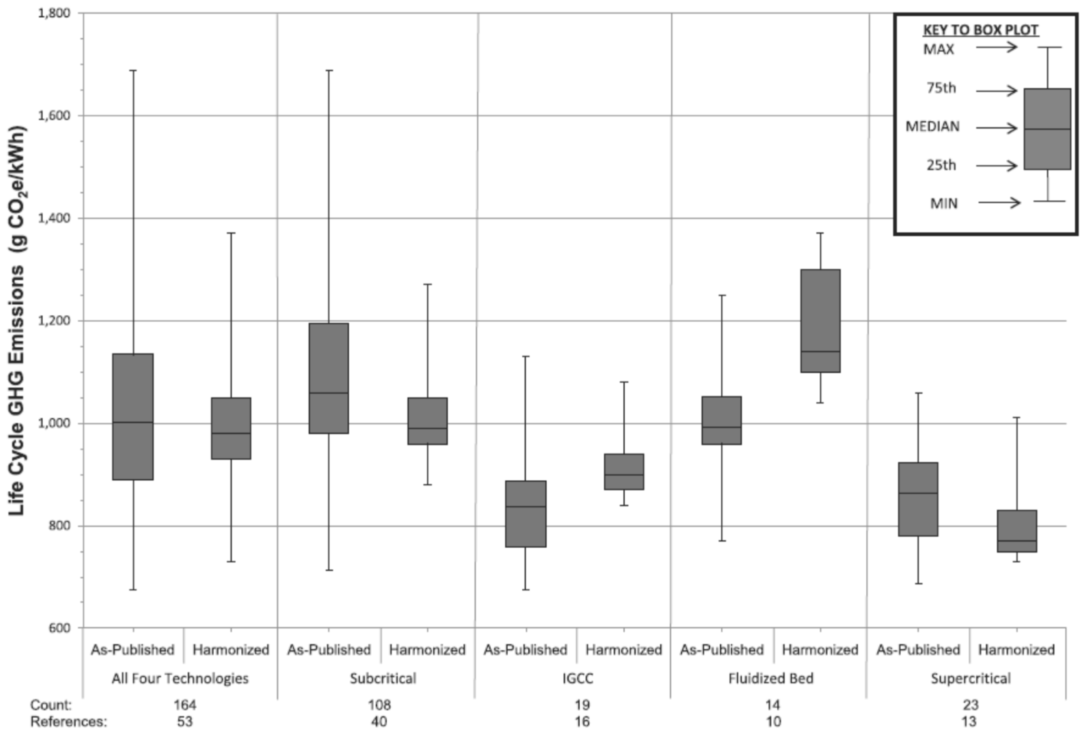



**Figure 39** Global Warming Potential (**GWP**) of coal-fired electricity[150].
IGCC = Integrated Gasification Combined Cycle.

[150] M. Whitaker *et al.*, "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation. Systematic Review and Harmonization" *J Ind Ecol*, vol. 16, no. S1, pp. S53-S72, 2012.
[151] E. S. Warner and G. A. Heath, "Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation. Systematic Review and Harmonization". *J Ind Ecol*, vol. 16, no. S1, pp. S73-S92, 2012.
[152] S. L. Dolan and G. A.Heath, "Life Cycle Greenhouse Gas Emissions of Utility-scale Wind Power. Systematic Review and Harmonization" *J Ind Ecol,* vol. 16, no. S1, pp. S136-S154, 2012.

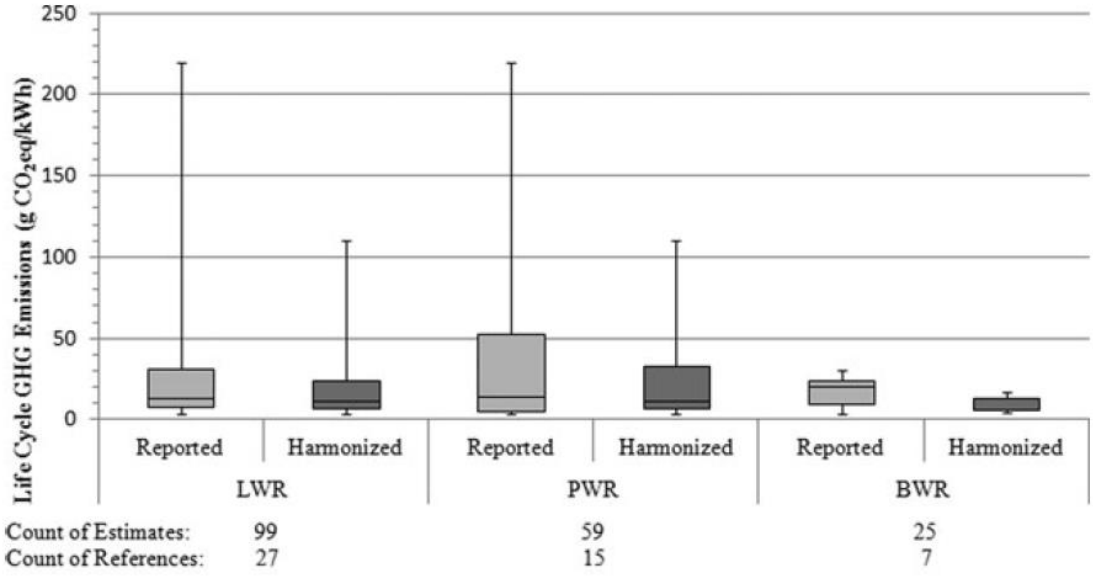



**Figure 40** Global Warming Potential (**GWP**) of nuclear electricity[151].
LWR = Light Water Reactor; PWR = Pressurised Water Reactor; BWR = Boiling Water Reactor.

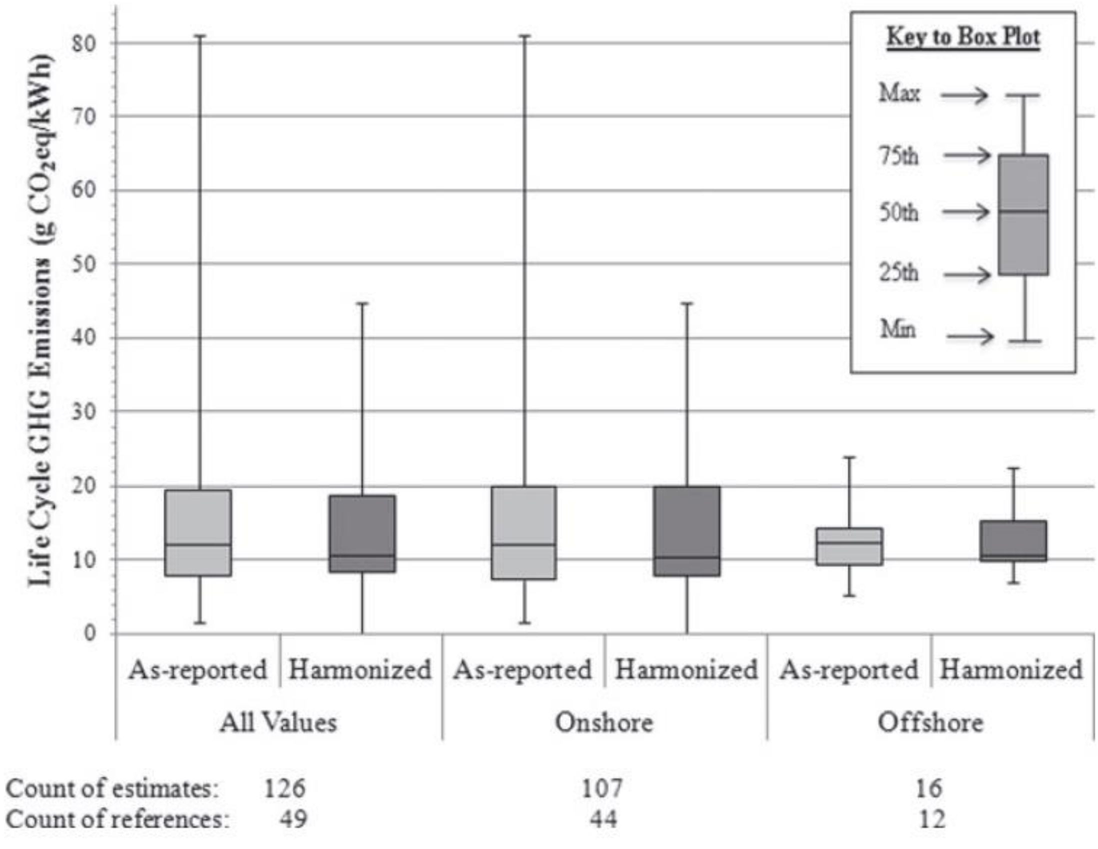



**Figure 41** Global Warming Potential (**GWP**) of wind electricity[152].

As further highlighted in Figure 42, while the comparison with coal-fired electricity is staggering in terms of the sheer order-of-magnitude difference of the results in favour of CdTe PV, the comparisons to nuclear and wind electricity are perhaps even more illuminating.

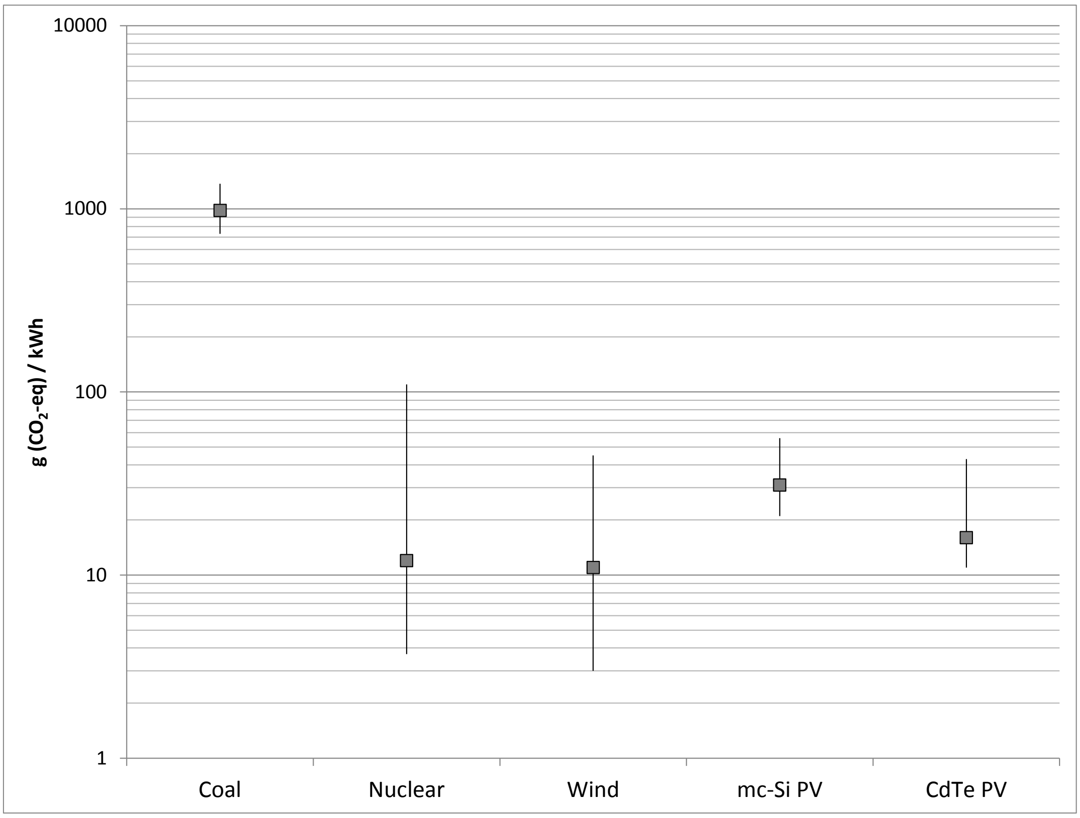



**Figure 42** Minimum, maximum and median harmonized literature values for Global Warming Potential (**GWP**) of coal-fired, nuclear, and wind electricity, compared to latest values for mc-Si PV and CdTe PV electricity[146], respectively for **Irr** = 1,000 kWh/(m$^2$·yr), **Irr** = 2,300 kWh/(m$^2$·yr) and **Irr** = 1,700 kWh/(m$^2$·yr).

Under optimal irradiation conditions, the life-cycle GHG emissions of current-generation CdTe PV essentially match the median levels reported for these two low-carbon technologies, at approximately 10 g($CO_2$-eq)/kWh$_{el}$, and even under a more average solar irradiation of 1,700 kWh/(m$^2$·yr), the GWP value for CdTe PV remains within the 75$^{th}$ percentile of those for nuclear and wind. Also, it is interesting to note that the variation in the reported results for the latter two technologies, even when harmonized, leads to an overall range that in some cases reaches considerably higher emission levels than those for CdTe PV, even under the least favourable irradiation condition of 1,000 kWh/(m$^2$·yr).

### 2.4.2.- MATERIAL FLOWS AND HEAVY METAL EMISSIONS

The production and use of cadmium (Cd) have long been the object of understandable concern, because of the metal's well-known toxicity. It is therefore important to review the available information on the actual intensity of the Cd flows associated to the life cycle of CdTe PV, and especially to discuss the latter against the backdrop of the yearly direct and indirect Cd flows that routinely take place within Europe due to all uses of the metal combined.

Cadmium sulfide (CdS) is virtually the only chemical form in which Cd appears in nature in concentrated form, and it is not generally present in significant quantities in isolated deposits on its own, but it is nearly always associated with zinc sulfide (sphalerite). As a consequence, zinc mines are the principal economically viable source of cadmium (approximately 97% of primary

Cd production). In fact, Zn producers do not have the option of not mining Cd, and, since the global production of Zn has increased much faster than the corresponding demand for Cd, the annual amounts of raw Cd generated are already entirely determined by Zn production rates[153].

In the literature, detailed material flow analyses of Cd are available for two among the world's most prominent countries in terms of overall Cd production[154], namely South Korea[155] and Japan[156]. Both studies agree in identifying a potential Cd oversupply problem for the near future, because of the linked nature of Cd and Zn production.

All three cited studies also agree in reporting that the largest use of Cd by far is still that for NiCd batteries, followed by its use in pigments, plating and plastic stabilizers, whereas CdTe PV systems do not yet attract a significant share of total Cd production. In particular, First Solar currently uses < 1% of global Cd production (i.e., ~150 tonnes Cd/yr, based on: 6 g Cd content per module[95], 16% module efficiency and 0.72 m2 per module, and 3GW/yr production).

Incidentally, this overall demand ranking is consistent with that produced by a previous world-wide report by UNEP[157].

One first very important distinction needs to be made between these different commercial uses of Cd. While, on one hand, the Cd contained in NiCd batteries and CdTe PV is fully enclosed and may - at least in principle - be recycled to a large extent at the product's end of life (*cf.* 2.4.6.- for current achievable Cd recovery rates from CdTe PV), on the other hand, Cd applications for pigments, metal plating and plastic stabilizing are intrinsically dispersive, which makes recovering the Cd at end-of-life of the related products and preventing it from entering the environment as a pollutant all but impossible. Moreover, there are a number of other relevant sources of indirect Cd emissions that need to be taken into account, among which are coal- and oil-fired power plants (where Cd is present in the feedstock fuels as an impurity), iron and steel manufacturing, non-ferrous metal production, and phosphate fertilizer production[158].

Overall, the most recent figures for the total Cd emissions to air and water within the EU-27 point to ~400 and ~50 tonnes (Cd)/year, respectively[158].

The overall Cd emissions from the life cycle of CdTe PV (excluding EoL) were quantified at approximately 300 mg/GWh for first generation modules operating at 9% efficiency and PR = 0.8 under 1,700 kWh/($m^2$·yr) irradiation[159]. In first approximation, the higher efficiency of current-generation CdTe PV modules (15.6%) already proportionally reduce the total Cd emissions to

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[153] M. Raugei and V. Fthenakis, "Cadmium flows and emissions from CdTe PV: future expectations," *Energy Policy*, vol. 38, no. 9, pp. 5223-5228, 2010.
[154] United States Geological Survey (USGS), 2016a. Mineral commodity summary: Cadmium. Available on line at http://minerals.usgs.gov/minerals/pubs/commodity/cadmium/mcs-2016-cadmi.pdf
[155] K. Cha *et al.*, "Substance flow analysis of cadmium in Korea," *Res Cons and Rec*, vol. 71, pp. 31-39, 2013.
[156] Y. Matsuno *et al.*, "Dynamic modeling of cadmium substance flow with zinc and steel demand in Japan*," Res, Cons and Rec*, vol. 61, pp. 83-90, 2012.
[157] United Nations Environment Programme (UNEP), 2006. Interim review of scientific information on cadmium. Available on line at http://www.unep.org/chemicalsandwaste/Portals/9/Lead_Cadmium/docs/Interim_reviews/UNEP_Cadmium_review_Interim_Oct2006.pdf
[158] M. Raugei, "Prospective Analysis of the Future Impact of CdTe PV in Terms of Cd Demand and Cd Emissions," in *23rd European Photovoltaic Solar Energy Conference and Exhibition (EU-PVSEC)*, Valencia, Spain, 2008.
[159] V. M. Fthenakis *et al*., "Emissions from photovoltaic life cycles," *Environ. Sci. Technol.*, vol. 42, pp. 2168–2174, 2008.

~170 mg/GWh. Further reductions are then due to improved manufacturing processes: Fthenakis[161] assumed 0.042 mg Cd/m$^2$ direct air emissions from CdTe PV manufacturing, whereas First Solar[160] now documents 0.00956 mg Cd/m$^2$. Crucially, however, less than 10% of the cumulative life-cycle Cd emissions were found to be related to the Cd actually contained in the PV modules[161], while the rest was due to the indirect Cd emissions caused by the fossil fuel electricity used in the PV manufacturing processes. Reduced electricity consumption during manufacturing and a shift to more renewable grid mixtures are therefore further potential sources of improvement. Finally, virtually no Cd emissions were found to occur in the use phase, even in the case of accidental fires[162], since the Cd is only present as chemically stable compounds (i.e. CdTe and CdS or CdSe) that are enclosed and sealed within glass panes.

But even without considering all these recent improvements, the life-cycle Cd emission figures for CdTe PV were already found to compare very favourably with those that are typical for most other electricity generation technologies[159], as shown in Figure 43.

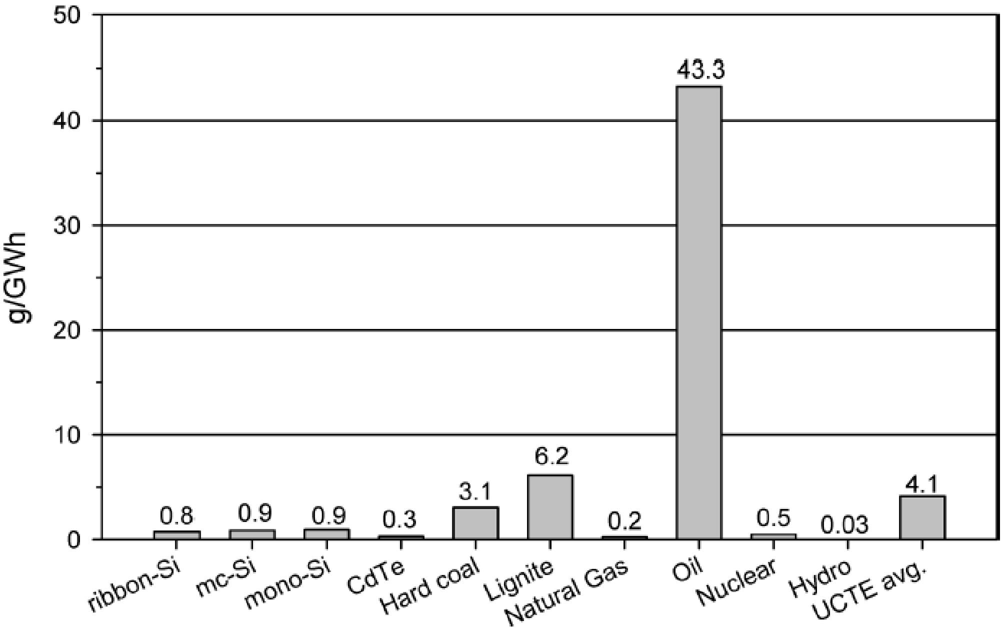


**Figure 43** Life-cycle Cd emissions of electricity generation technologies[159].
Assumptions for CdTe PV are **η = 9%**, **T = 30** yr, **PR** = **0.8** and **Irr** = **1,700** kWh/(m$^2$·yr).

In view of all of the above, a future increase in the demand for Cd for its use in CdTe PV has been identified as potentially beneficial to the environment, as it would provide a viable and comparatively safe and easy-to-recycle temporary sequestration route for the expected oversupply of raw Cd[155,156]. (Theoretically, leaving the Cd immobilized in the ore deposits in the ground would of course be the most preferable strategy of all, from an ecological point of view. However, because of the growing demand for Zn, and the fact that Cd is indissolubly co-present

[160] First Solar Series 4 PV System Product Environmental Footprint.
[161] V. M. Fthenakis, 2004. "Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production," *Ren. Sust. Energy Rev.* vol. 8, pp. 303-334, 2004.
[162] V. M. Fthenakis *et al*., "Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires," *Prog. Photovolt: Res. Appl.,* vol. 13, no. 8, pp. 713-723, 2005.

in the same ore deposits, this is unfortunately not possible at all. Developing a costly strategy for the safe long-term sequestration for Cd post-extraction at the mining sites themselves is also hardly feasible, given the lack of economic incentives to do so).

Finally, to put the whole Cd issue into perspective, a literature study[153] estimated the potential future cumulative Cd emissions due to a massive 1 $TW_p$ worldwide deployment of CdTe PV in 2050, and compared it to the current routine yearly emissions taking place within the EU-27 in the year 2010. Remarkably, the former were found to be two orders of magnitude lower than the latter, as illustrated in Figure 44. This comparison fails to take into account the expected future changes in Cd emissions due to e.g. a projected progressive decarbonisation of electricity in the EU, and therefore it should not be taken as a quantitative indication of the expected ratio of the *future* Cd emissions by CdTe PV to the *future* overall Cd emissions in the EU. However, it still serves its originally intended purpose of highlighting how comparatively small the total Cd emissions ascribable to even a large deployment of CdTe PV could be, when set within the broader context of the historical cumulative Cd flows to air, water and soil that have routinely taken place on a yearly basis until now.

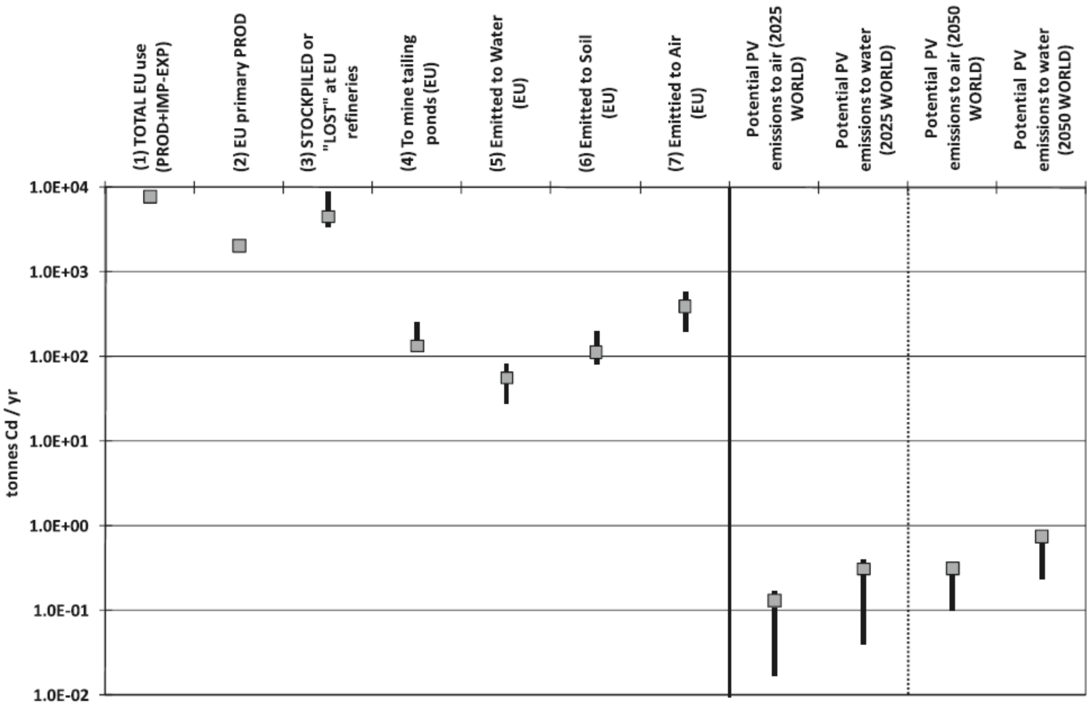


**Figure 44** Current Cd flows in EU-27 compared to potential future global Cd emissions caused by CdTe PV (logarithmic scale)[153]. Assumed maximum cumulative capacities are 260 $GW_p$ in 2025 and 1 $TW_p$ in 2050.

### 2.4.3.- RAW MATERIALS AVAILABILITY

As the name implies, two elements are critical to the functioning of CdTe PV, namely the metal cadmium (Cd) and the metalloid tellurium (Te).

As discussed in section 2.4.2.- Cd availability does not represent a constraint on the future large-scale deployment of CdTe PV – quite on the contrary, it is the latter that has the potential to contribute to reducing the problem of Cd oversupply.

On the other hand, long-term Te availability poses more of a potential issue that is worth investigating, given that CdTe PV production is already responsible for a large share of the global Te demand worldwide[163,164].

The main commercially exploitable source of primary Te is the processing of the anode slimes from copper (Cu) mining. Primary Te ores have also been identified and are exploited commercially in China and Sweden, providing approximately 15% of the total world supply[165,164] Finally, recovery of Te from ocean bed deposits of volcanogenic massive sulfides has also been identified as a future theoretical possibility; however the feasibility of the commercial exploitation of this third source of the metalloid is still debated[165].

A number of recent studies[163,166,167,168,169] have looked into the potential issue posed by limited Te availability by developing suitable long-term scenarios that take into account a range of parameters, including:

(i) increased availability of Te due to improved recovery from primary sources;

(ii) projected CdTe PV technological improvements in terms of reduced CdTe layer thickness and improved module efficiency; and

(iii) large-scale recycling of Te from CdTe PV end-of-life.

The most recent of these calculations[169] point to almost linearly increasing maximum Te-constrained annual installed CdTe PV capacities beyond 2020, reaching (150 - 250) $GW_p$/yr in 2050 (and corresponding to a cumulative installed capacity of (2 - 4) $TW_p$ by the same year), respectively according to 'reference' and 'optimistic' sets of assumptions on parameters (i), (ii) and (iii) above.

In light of these results, it appears reasonable to conclude that CdTe PV may be expected to play a prominent role as a major renewable energy enabler before the Te availability issue becomes a significant constraint.

Finally, looking beyond the two key technology-specific elements Cd and Te, a potential long-term constraint on the large-scale deployment of all PV technologies - including but not exclusive to CdTe PV - has been identified in the demand for copper, which is required for the associated electrical BoS components, including cabling, inverters and transformers[142,144,170,171].

[163] K. Zweibel, "The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics," *Science* vol. 328, pp. 699-701, 2010.
[164] *United States Geological Survey (USGS), Mineral commodity summary: Tellurium*. Available on line at http://minerals.usgs.gov/minerals/pubs/commodity/selenium/mcs-2016-tellu.pdf
[165] *United States Geological Survey (USGS), Tellurium - The Bright Future of Solar Energy*. Available on line at https://pubs.usgs.gov/fs/2014/3077/pdf/fs2014-3077.pdf
[166] C. S. Tao *et al*., "Natural resource limitations to terawatt-scale solar cells," *Solar Energy Mat & Solar Cells* vol. 95, pp. 3176-3180, 2011.
[167] V. M. Fthenakis, "Sustainability metrics for extending thin-film photovoltaics to terawatt levels," *MRS BULLETIN* vol. 37, pp. 425-430. 2012.
[168] M. Redlinger *et al*., "Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules," *Solar Energy Materials and Solar Cells*, vol. 138, pp. 58–71, 2015.
[169] Y. J. Houari *et al*., "A system dynamics model of tellurium availability for CdTe PV," *Prog. Photovolt: Res. Appl*., vol. 22, no. 1, pp. 129-146, 2014.
[170] It is noteworthy that inverters and transformers scale with the power rating of the PV system, so increasing module efficiency does not reduce demand for metals by inverters and transformers.

On average, per unit of generated electricity, PV systems require between 11 and 40 times as much Cu as conventional fossil fuel-based thermal systems[144], and it has been calculated that in order to produce enough PVs to supply 2.7% of the projected demand for electricity in the USA in the year 2030 would require over 50% of all the Cu that was domestically refined in 2013[142].

Taken at face value, this is certainly a worrying result – however, it must be borne in mind that it was calculated without accounting for any material recovery at end-of-life (EoL). In reality, a large share of the Cu contained in the BoS of decommissioned PV systems may be easily recycled (*cf.* 2.4.6.-), which, in the long run, would contribute to reducing the overall demand for primary Cu. In fact, a potential reduction of up to 52% in overall metal depletion per unit of generated electricity has been estimated to be attainable thanks to EoL recycling of the BoS[142].

### 2.4.4.- LAND USE AND BIODIVERSITY

When installed on rooftops – both in the case of residential and commercial buildings – PV systems clearly do not require any additional land, nor do they have any direct effect on biodiversity (whereas indirectly, they may be beneficial if they displace other electricity generation technologies that instead do require earmarked land). On the other hand, in the case of utility-scale ground-mounted PV installations, the interrelated issues of overall land demand and potential ecological disturbance may not be so easily dismissed, and require more careful scrutiny.

Two metrics have been defined related to land use, namely **land transformation** (defined as the area of land that is altered from its original state, and measured in units of [$km^2$/GWh]), and **land occupation** (which takes into account the duration of the time frame during which the land is occupied, before it is eventually returned to its original state, and which is measured in units of [($km^2$·yr)/GWh]).

While the former metric is relatively straightforward in its definition, the latter entails a value judgement as to the degree of land and ecological restoration that is deemed sufficient to restore the pre-existing conditions (a goal which may or may not be fully achievable, depending on the type of transformation that the land was subject to, to begin with). In this sense, the site preparation operations required for the installation of ground-mounted CdTe PV systems (especially the "light-on-land" techniques employed by First Solar[172]) pave the way to a much easier (and quicker) restoration process down the road than, for instance, the very aggressive mountaintop removal operations required for the surface mining of the coal seams that supply the feedstock to many thermal power plants.

Methodologically, the calculation of these two land use metrics requires a number of assumptions, which need to be considered carefully if consistent comparisons are sought, and

[171] M. D. Chatzisideris *et al*., "Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies," *Solar Energy Mat and Solar Cells* (in press). Available in http://dx.doi.org/10.1016/j.solmat.2016.05.048.
[172] First Solar's Sustainability report, 2016. Available online at http://www.firstsolar.com

which inevitably lead to ranges of results (rather than precise numbers):

1. System lifetime;
2. Direct land area used for the generating facilities (e.g., the PV plant, or the coal-fired power plant);
3. Indirect land area used for the manufacturing of the generating facilities;
4. Indirect land area used for the harvesting, transportation and refinement of the feedstock fuel (this only applies to thermal electricity systems);

and, in the case of **land occupation**, also:

5. Time necessary for the recovery of the land transformed (this may be hard to quantify for some fuel cycles, such as e.g. surface-mined coal and nuclear).

The potential impacts on biodiversity are then even harder to quantify, since they depend on a wide range of site-specific conditions that do not lend themselves to sweeping generalizations. However, such impacts may still be estimated by providing qualitative indications on the expected comparative impacts of alternative technologies.

While not considering CdTe PV explicitly, two relatively recent literature studies are nonetheless very relevant in addressing the issues of land use and biodiversity impacts and in providing a balanced comparison of the performance of PVs *vs*. that of alternative electricity generation technologies[173,174].

In the former study, a comparative graph of the land transformation associated with a range of electricity generation technologies is provided (see Figure 45 below). These results highlight the fact that, despite some common misconceptions about the perceived more 'dilute' nature of renewable energy, and of solar PV in particular, the land transformation per unit of generated PV electricity is actually very similar to that of conventional electricity produced from coal and nuclear feedstocks, when duly taking into account all indirect land uses (as per points 3 and 4 above). Also, PV is shown to compare favourably to other renewables like wind (which is characterised by approximately double land transformation figures), and especially hydro and biomass-fired electricity.

[173] V. Fthenakis and H. C. Kim, "Land use and electricity generation: A life-cycle analysis," *Ren Sust En Rev* 13:1465–1474, 2009.
[174] D. Turney and V. Fthenakis, "Environmental impacts from the installation and operation of large-scale solar power plants," *Ren Sust En Rev*, vol. 15, pp. 3261–3270, 2011.

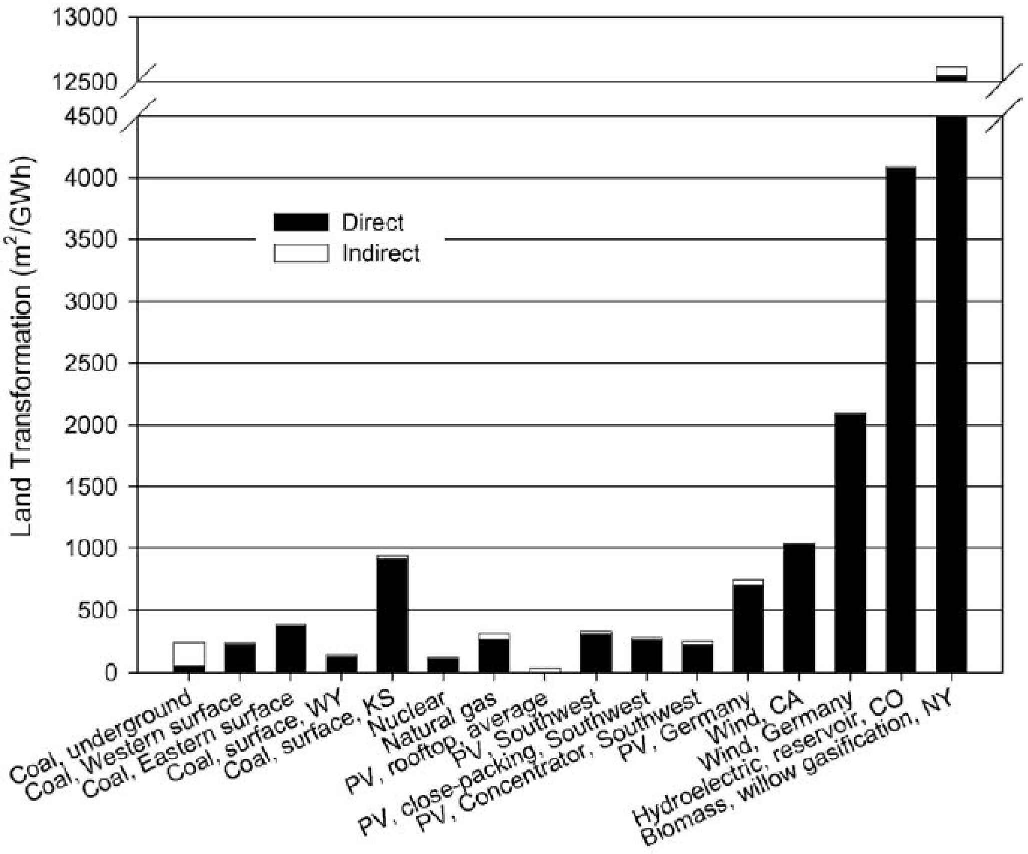


**Figure 45** Land transformation for a range of electricity generation technologies[173]. Assumptions for PV are **η = 13%**, **T = 30** yr, **PR** = **0.8**, **Irr** = **1,800** kWh/($m^2$·yr) for "rooftop, average", and **Irr** = **2,400** kWh/($m^2$·yr) for "Southwest".

Turney and Fthenakis[174] then report an interesting analysis of land transformation and land occupation metrics for PV and coal-fired electricity, as a function of power plant lifetime (Figure 46). Interestingly, while neither metric is significantly affected by plant lifetime in the case of coal electricity (because the main contribution is due to the indirect area required for coal mining), the performance of PV electricity continues to improve as the PV system's lifetime is extended, potentially leading to even lower land transformation and occupation values per unit of output.

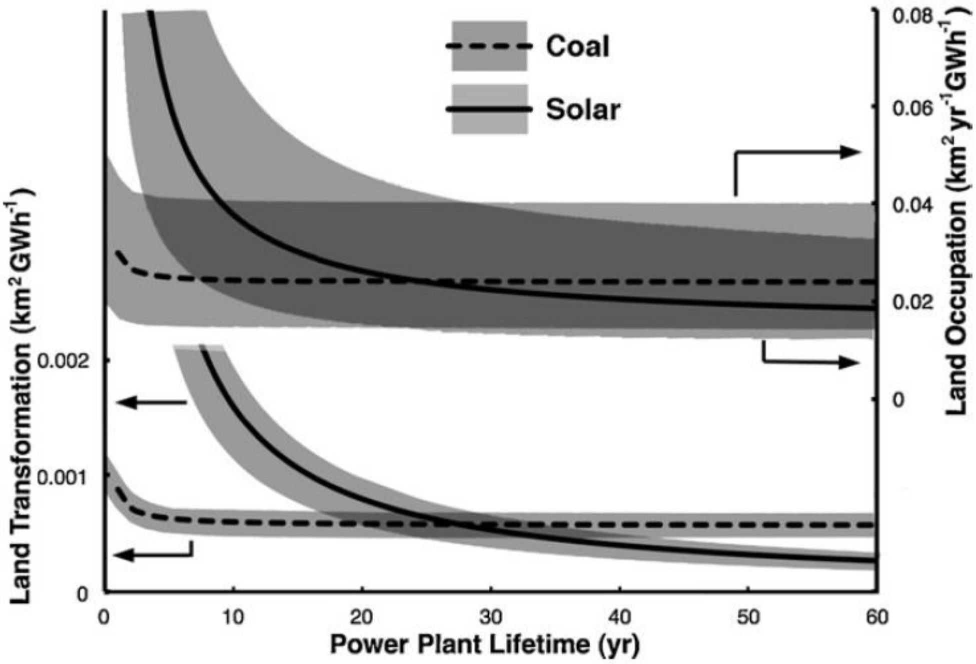


**Figure 46** Land transformation and land occupation for PV and coal-fired electricity[174].
Assumptions for PV are **η = 13%**, **PR** = **0.8**, **Irr** = **1,700** kWh/($m^2$·yr).

Also, in the same reference a wide range of qualitative criteria are assessed with regards to the potential impacts on biodiversity, including exposure to hazardous chemicals, physical dangers (such as roadway hazards and flight hazards for birds), and habitat loss and fragmentation. Out of a total of twelve criteria, only one was found to be negatively impacted by the deployment of PV systems (increased flight hazard for birds due to the requirement for new transmission lines), while two were considered neutral, and nine were found to be improved by PV with respect to the current conventional ways of generating electricity in the USA.

It is worth mentioning that, while the cited studies date back to respectively 2009 and 2010, they are still the most recent available references that compare the performance of PV to other electricity generation options from the points of view of land use and biodiversity impacts. Additionally, given the recent significant improvements in terms of PV module efficiency (*cf.* Figure 5), the comparative performance of CdTe PV - when expressed per kWh of electricity produced - may be expected to have improved even further.

Also, a 2010 report by the German Renewable Energy Agencies[175] concluded that "with the right measures in place, solar parks can promote and conserve biodiversity". The report provides a detailed list of such "right measures", organized into three main sections: measures to be implemented during planning, construction and operation.

Measures during planning start with the selection of suitable sites that are not critical in terms of biological diversity in the first place, and may even entail the rehabilitation of contaminated sites,

[175] T. Peschel, "Solar parks – Opportunities for Biodiversity: A report on biodiversity in and around ground-mounted photovoltaic plants," German Renewable Energies Agency, Berlin, Germay , Issue 45, ISSN 2190-3581, 2010.

such as brownfields, previously used for military or industrial purposes.

Measures during construction include minimization of soil sealing. Additional recommended measures during construction include the provision of 'buffer' zones around the PV field, of suitable gaps in the fencing to allow the passage of small animals, and, where appropriate, compensatory measures such as the relocation of endangered flora and the purposeful planting of shrubs and seed mixtures to provide enhanced micro-habitats.

Finally, continuous monitoring of the sites during operation is recommended in order to build a robust body of evidence on any unforeseen adverse effects (or lack thereof) on the flora and fauna.

First Solar's documented practice in terms of the construction of utility-scale PV power plants thus far appears to be essentially in line with all the recommended measures discussed above[172]. In particular, careful site selection has been a priority and the product of extensive reviews. In at least one case in Germany, this entailed a major clean-up of previously contaminated land.

Also, while in the past the designated sites for PV power plants were quasi-bulldozed in order to obtain a levelled installation surface, First Solar adopts much "lighter on land" techniques such as disk-and-roll and mowing so as to retain soil fertility and minimize soil erosion. Specifically, the disk-and-roll technique mainly follows the natural pattern of the environment, and only large obstacles are removed and/or adjusted. The environmental impact of this technique is therefore much smaller.

Species relocation programmes have also been put in place when deemed appropriate (e.g. in Chile). Finally, in North America, to compensate for any unavoidable impacts to habitats, First Solar has often adopted compensatory measures by either directly purchasing land in order to protect it, or arranging for third parties to acquire control of properties for conservation.

### 2.4.5.- WATER USE

Perhaps somewhat surprisingly (given that water bodies cover 70% of the surface of the Earth, and that our own bodies are made up of water by a similar percentage), freshwater is actually a rather scarce resource, since 97% of the total water on the planet is saltwater, and approximately two thirds of the remaining 3% is locked up in glaciers and in the ice caps[176].

It is therefore important to monitor the use of freshwater throughout the life cycle of all human-dominated processes, and specifically of those comprising the energy sector. The water use issue is then arguably even more relevant for PVs, since the better insolated areas of the world where the latter are likely to be preferentially deployed are also typically more arid. Unlike thermal power plants, solar PV generates electricity without the use of water and can therefore provide a solution to the energy-water nexus.

With this in mind, it is important to not only calculate the overall life-cycle water use of CdTe PV,

[176] World Wide Fund for Nature (WWF), 2016. *Water scarcity*. Available: http://www.worldwildlife.org/threats/water-scarcity

but also to compare it to that of alternative electricity generation technologies, and of the electric grid mixes of the regions where PV is to be deployed.

From a methodological perspective, a distinction needs to be made between **water withdrawal** (the amount of water removed from all sources over a system's life cycle) and **water consumption**; the latter is derived from the former by subtracting all water that is discharged by the analysed system back into its immediate surroundings.

Fthenakis and Kim[177] calculated a life-cycle (excluding EoL) water withdrawal figure of 800 L/MWh for ground-mounted CdTe PV systems with a module efficiency of 10.9%, a system lifetime of 30 years and a PR = 0.8, when installed under average US irradiation of 1,800 kWh/($m^2$·yr). Their comparison with other electricity generation technologies, reproduced here in Figure 47, indicated that in terms of water use, the performance of CdTe PV was the third best across the board, after only wind and hydro-electricity (according to convention, the latter was estimated without accounting for the water that actually flows through the turbines). It is noteworthy that while this study dates back to 2010, a more recent review and harmonization study[178] essentially confirmed the same ranges of values for most technologies, with the only notable exception of a lower mean estimate for PVs (but the authors acknowledge "uncertainty" and combine "a variety of PV technologies, mostly thin films" into a single category).

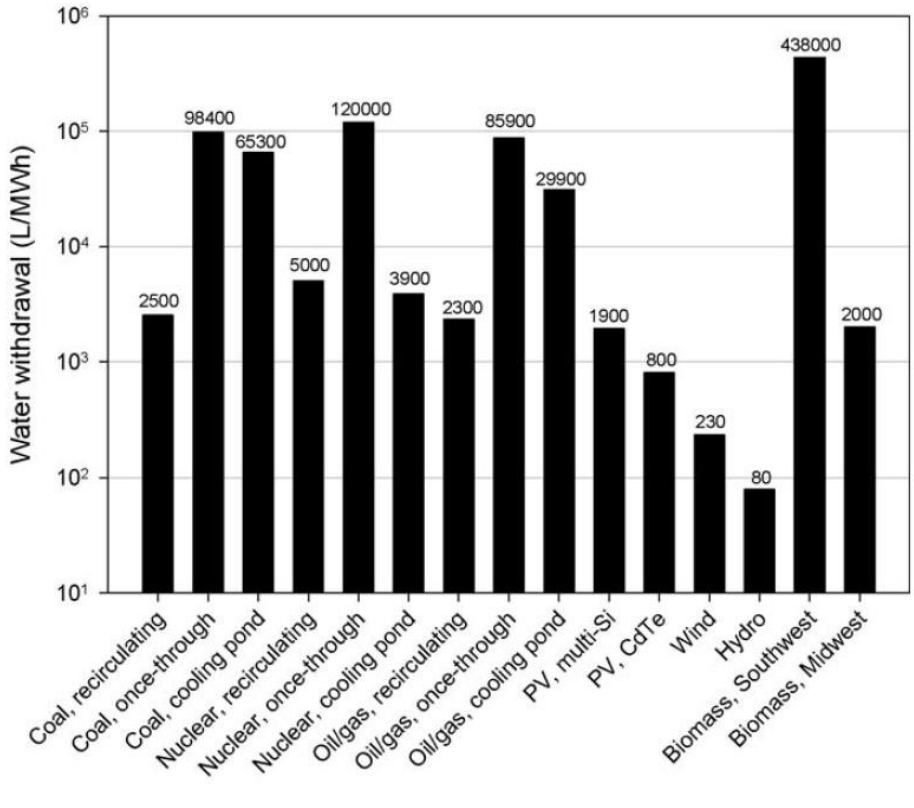


**Figure 47** Life-cycle water withdrawal of electricity generation technologies[177].
Assumptions for CdTe PV are **η = 10.9%**, **T = 30** yr, **PR** = **0.8** and **Irr** = **1,800** kWh/($m^2$·yr).

[177] V. Fthenakis and H. C. Kim, "Life-cycle uses of water in U.S. electricity generation," *Ren Sust En Rev*, vol. 14, pp. 2039–2048, 2010.
[178] Meldrum J., *et al.*, "Life cycle water use for electricity generation: a review and harminization of literature estimates". *Env. Res. Letters*, vol. 8, 2013.

A more recent study by Sinha *et al.*[179] then looked at water usage by CdTe PV in isolation, using updated production data and module efficiencies (12.2%). The results of this study are not directly comparable to the previous ones, though, since EoL take-back and recycling was also included in the analysis, and a higher irradiation level of 2,199 kWh/(m$^2$·yr) was assumed (which was indicative of the planned siting of the analysed CdTe PV system in California, and would also be typical of Southern European sites such as Greece and the South of Spain). A sensitivity analysis was also performed whereby the lifetime of the BoS ($\mathbf{T_{BOS}}$) was allowed to vary from 30 years (i.e., the same as that of the PV modules) to 60 years, leading to a corresponding range of results.

As shown in Table 10, excluding the EoL and harmonizing the latter study's results to **Irr** = 1,800 kWh/(m$^2$·yr) and $\mathbf{T_{BOS}}$ = 30 yr leads to a rather impressive halving of the water withdrawal for the CdTe modules, with respect to the previous results; the total life-cycle water withdrawal of the PV system (excluding EoL) is also reduced by 43%.

It is interesting to note that starting with the 2010 results and just increasing the module efficiency from 10.9% to 12.2% would only lead to an 11% reduction in water withdrawal. Study A utilizes data from Table 1 of a previous publication[180], which documents 300 kg of water per m$^2$ of CdTe PV module manufactured, whereas Table II of Study B documents 182.8 kg of water per m$^2$ of CdTe PV module manufactured, which means that part of the improvements can also be traced to the manufacturing process. Additionally, there may also be differences in the underlying electricity mixes, as Study B assumed manufacturing in the USA, Germany, and Malaysia, whereas Study A only focused on the USA.

| Ref. | (A) Fthenakis and Kim, 2010 | (B) Sinha *et al.*, 2012 (as published) | (C) Sinha *et al.*, 2012 (harmonized) | % Difference btw. (C) and (A) |
|---|---|---|---|---|
| η | 10.9% | 12.2% | 12.2% | |
| Irr [kWh/(m$^2$·yr)] | 1,800 | 2,199 | 1,800 | |
| CdTe modules | 576 L/MWh | 224 L/MWh | 274 L/MWh | -52% |
| BOS | 212 L/MWh | (106 - 150) L/MWh[a] | 183 L/MWh | -13% |
| Use phase | 15 L/MWh | - | - | |
| EoL | - | 51 L/MWh | - | |
| TOTAL | 803 | (381 - 425) L/MWh | 457 L/MWh | -43% |

**Table 10** Water withdrawal results for ground-mounted CdTe PV systems.

[a] Range corresponds to assuming BoS lifetime ($T_{BOS}$) = (60 - 30) yr.

[179] P. Sinha *et al.*, "Life Cycle Water Usage in CdTe Photovoltaics," *IEEE Journal of Photovoltaics,* vol. 3, no. 1, pp. 29-432, 2012.
[180] Fthenakis VM, Kim HC., "Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics". In: Materials research society symposium Proceedings. 2006

Sinha *et al*.[179] also calculated that, when deployed in the US Southwest, CdTe PV arrays could displace water withdrawal from the existing California grid electricity by as much as (1,700 - 5,600) L/MWh.

Finally, as regards the management of wastewater from the CdTe PV module manufacturing processes, all First Solar facilities are characterized by state-of-the-art performance that is beyond even the very strict standards imposed by the regulations that are in place in Malaysia (which are among the strictest in the world). First Solar facilities are equipped with very sensitive analytical equipment for in-house water testing of heavy metals (including Cd). As a result, all treated wastewater is pure enough to be directly discharged to the environment[172] (in reality, only the Malaysia facility directly discharges treated wastewater to river. The other facilities discharge to sewer, but all facilities have similar wastewater treatment technology and discharge water quality).

### 2.4.6.- PRODUCT END-OF-LIFE AND RECYCLING

Even though only a negligible share of the CdTe PV installed capacity so far has reached its designated end of life, assessing the environmental consequences of this last stage of a CdTe PV system's life cycle is already important in order to identify any future criticalities and to estimate the potential energy and environmental benefits ensuing from the recovery of recycled materials.

The recycling of the main structural components of the BoS such as steel and aluminium parts does not present any particular technological hurdles, and may be assumed to be performed in a similar way as has already become commonplace in many other industries (current average recovery rates for steel and aluminium have been reported at 90% and 79%, respectively[181]). Copper contained in electrical BoS components such as cabling and inverters are also expected to be recoverable and recyclable to a large extent (76%[181]) using existing methods.

The recycling of the CdTe PV modules themselves, instead, requires dedicated technology, and First Solar has been at the forefront of developing this, having established the first global and comprehensive module recycling program in the PV industry already in 2005. A detailed description and flowchart of First Solar's CdTe PV module recycling were provided in section 2.3.2.3.-

First Solar's module recycling process already performs beyond the requirements of the Waste Electrical and Electronic Equipment (WEEE) directive of the European Union [EC Directive 2012/19/EU[182]] in terms of bulk recovery rates[183].

However, an additional driver in developing and continuing to improve the process is the fact that, in the long-term, large-scale recycling is also expected to play a key role in ensuring the

[181] M. Classen *et al.*, "Life Cycle Inventories of Metals," Final report ecoinvent data v2.1, no. 10.; Ecoinvent Centre: Dübendorf, Switzerland, 2009.
[182] European Commission Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE).
[183] The current WEEE bulk recovery and recycling targets are respectively 80% and 70%.

sustained availability of scarce yet technology-enabling inputs such as Te[184,168].

During the EoL recovery and recycling process, the incineration of combustible materials such as the cable sheathing and the plastic encapsulation foil allows for the straightforward recovery of a significant amount of energy.

Calculating the energy and environmental 'credits' associated with EoL material recycling is more complicated from a methodological perspective, and two approaches have been proposed in the literature, respectively referred to as the 'Recycled Content' (RC) and the 'End Of Life Recycling' (EOLR) approaches[185].

These two opposite allocation options are illustrated in Figure 48 for the idealized case of two daisy-chained product systems of which the first one (designated as System 1) makes exclusive use of primary materials and the second one (System 2) uses the recycled materials from the end of life of the first one. Of course, real cases are never quite as simple and straightforward, since real product systems may employ a mix of primary and recycled materials, and they usually have multiple parts that can be recycled to various degrees, complicating the situation even further.

In the 'RC' approach, all the energy and environmental burdens associated with the recycling processes are assigned to System 2. Operating this way corresponds to imposing a clear 'cut-off' between the two systems as indicated by the dashed horizontal red line, and consequently calculating the life-cycle impacts of System 1 *excluding* EoL recycling.

An alternative possibility is to adopt the EOLR approach, wherein System 1 is assigned all the energy and environmental burdens associated with the recycling processes. In this second allocation option, energy and environmental 'credits' are also assigned to System 1, corresponding with the avoided impacts of producing the virgin materials that are potentially displaced (thereby realising a virtual 'closed loop' recycling scheme, as indicated by the red arrow on the right-hand side of the diagram). This is due to the fact that recycled materials could (if they are recovered with a sufficient level of purity) potentially be employed *in lieu* of corresponding amounts of virgin materials in the production of System 1

The caveat in assigning these credits to System 1, however, is that in order to avoid inter-system double counting of the energy and environmental 'benefits' of recycling, the same recycled materials may then no longer be assessed as being used as inputs to System 2. As a result, in a fully consistent joint application of the EOLR approach to (System 1 + System 2), System 2 would end up being penalized by having to account for its (recycled) inputs as though they were virgin (as indicated by the blue arrow on the left-hand side of the diagram).

[184] M. Marwede and A. Reller, "Future recycling flows of tellurium from cadmium telluride photovoltaic waste," *Res, Cons and Rec,* vol. 69, pp. 35– 49, 2012.
[185] J. X. Johnson *et al*., "Evaluation of Life Cycle Assessment Recycling Allocation Methods. The Case Study of Aluminum," *J Ind Ecol,* vol. 17, no. 5, pp.70-711, 2013.

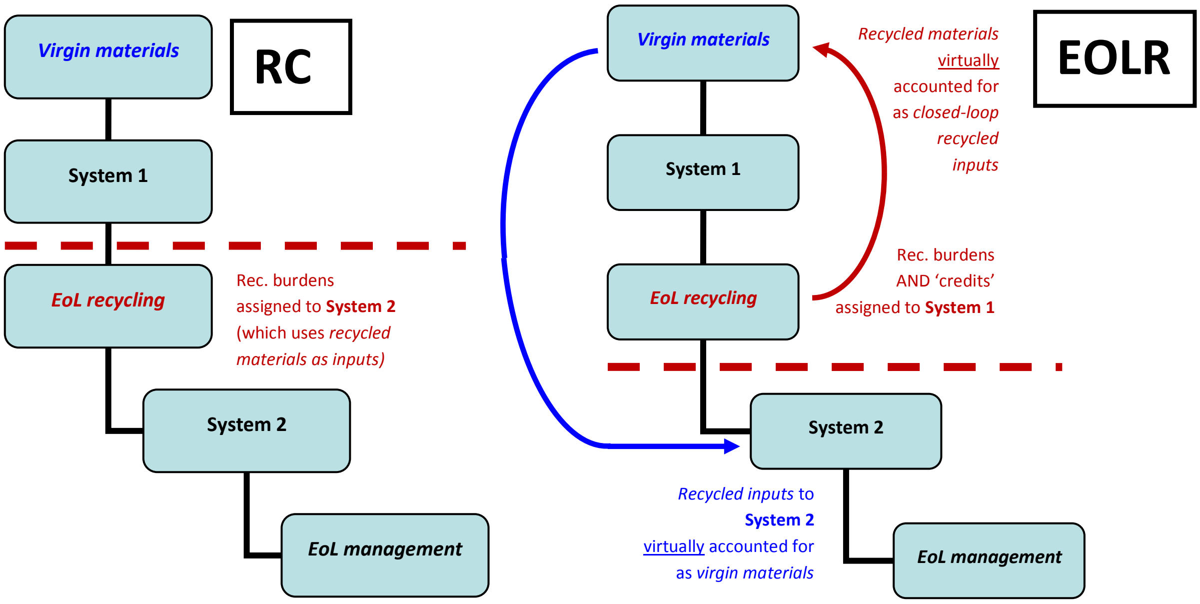


**Figure 48** Alternative allocation options for the assessment of end-of-life (EoL) recycling.

As discussed elsewhere[186], the RC approach may be thought of as the more 'cautious' of the two, since it accounts for all environmental impacts as they actually happen, without making any assumptions on the future fate of the recovered materials. Be that as it may, both allocation approaches can be argued to produce 'correct' results (provided that they are applied consistently throughout the product chain), and the methodological choice of which allocation option to adopt is ultimately more of a political - rather than scientific - nature.

As a way out of this conundrum, intermediate allocation options may be defined, whereby only a given fraction of the recycling 'credits' are assigned to the first product system, while the remainder is left for the subsequent one(s).

This latter choice was made in one of the surveyed studies addressing the issue of CdTe PV EoL recycling[145], where "potential future environmental benefits which result from recycling are allocated according to the formula provided in the recommendation of the European Commission[187]. 50% of the potential future environmental benefits are allocated to the PV system delivering the goods for recycling; the remaining 50% are allocated to the product system reusing the recycled goods in the future."

One other surveyed study[188], instead performed a sensitivity analysis by carrying out the calculations twice, alternatively adopting the EC and the EOLR approaches.

Finally, the remaining surveyed studies[189,137] only investigated the recycling of the PV modules

[186] R. Frischknecht, "LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency," *Int J Life Cycle Assess,* vol. 15, pp. 666-671, 2010.
[187] European Commission, 2013. European Commission (2013b) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union.
[188] D. Ravikumar *et al*., "An anticipatory approach to quantify energetics of recycling CdTe photovoltaic systems," *Prog. Photovolt: Res. Appl*., vol. 24, no. 5, pp. 735-746, 2016.
[189] M. Held, "Life Cycle Assessment of CdTe Module Recycling," *24th EU PVSEC Conference*, Hamburg, Germany. 2009.

(as opposed to the entire PV system), and simply adopted the EOLR approach *tout court* (albeit while still providing a detailed break-down of the impacts that allows the 'credits' to be easily identified).

In light of the last few paragraphs, it ought to be unsurprising that a simple and clear-cut calculation of the energy and environmental impacts and benefits of the EoL stage of CdTe PV is destined to remain somewhat elusive. However, it is important to note that in all surveyed studies the energy and emission 'credits' due to EoL recycling turned out to be larger than the impacts associated with the entire EoL management stage. This is an unequivocal indication of the beneficial effects of recycling, beyond the intrinsic benefit in terms of the sheer recovery of valuable (and in some cases scarce) materials. Also, Ravikumar *et al*.[188] showed that, under their most advanced recycling scenario and adopting the EOLR approach, the net energy benefit of EoL recycling "would result in a reduction in the energy payback time of the PV system comparable with increasing CdTe PV module conversion efficiency from its current[190] average value of 14% to over 18.42%".

At present, First Solar recycling facilities are operating in the USA, Germany, and Malaysia. Mobile recycling facilities are planned to be introduced in the near future, in order to reduce transportation impacts and costs[191].

### 2.4.7.- KEY IMPACTS OF LONG-TERM CdTe PV TECHNOLOGY DEPLOYMENT IN EUROPE

The following section will briefly discuss the key expected impacts of CdTe PV deployment in Europe in the medium term. To this aim, the annual CdTe PV modules installed in Europe until 2020 will be forecasted, from which, the yearly amount of Cd employed in the European PV installations will be estimated. Besides, the cumulative CdTe PV waste volumes in Europe and the recovery of Cd from the recycling activities in a long-term scenario are covered at the end of this section.

According to Solar Power Europe, the annual PV installations in Europe will increase from 8.47 GW in 2017 to 14.81 GW in 2020 (in the medium scenario)[192]. Assuming a constant market share of 4% for CdTe photovoltaics in Europe[193,194] the amount of CdTe PV installations will increase to approximately 600 MW, in 2020. Taking into account the reduction of Cd employed per kWp[153], the yearly amount of Cd used in CdTe PV modules in Europe can be calculated. As can be appreciated from Figure 49, the amount of Cd which may be expected to be used for CdTe PV modules in Europe will range from 43 tonnes in 2015 to more than 60 tonnes, in 2020. Just in order to provide some context for these numbers, global Cd production in 2015 was 24,200 tonnes/year while the total Cd emission to air and water within the EU-27 were reported to be approximately 400 tonnes/year and 50 tonnes/year respectively[153].

[190] "Current" at the time of writing. The actual current (2015) average module conversion efficiency is 15.5%.
[191] S. Raju, "First Solar's industry-leading PV technology and recycling program," presentation, Solar Power International Conference, Chicago. 2013.
[192] Michael Schmela *et al.,"*Global market Outlook for Solar Power/2016-2020", SolarPower Europe.
[193] Fraunhofer ISE: Photovoltaics Report, updated: 6 June 2016.
[194] NPD Solarbuzz, November 2014

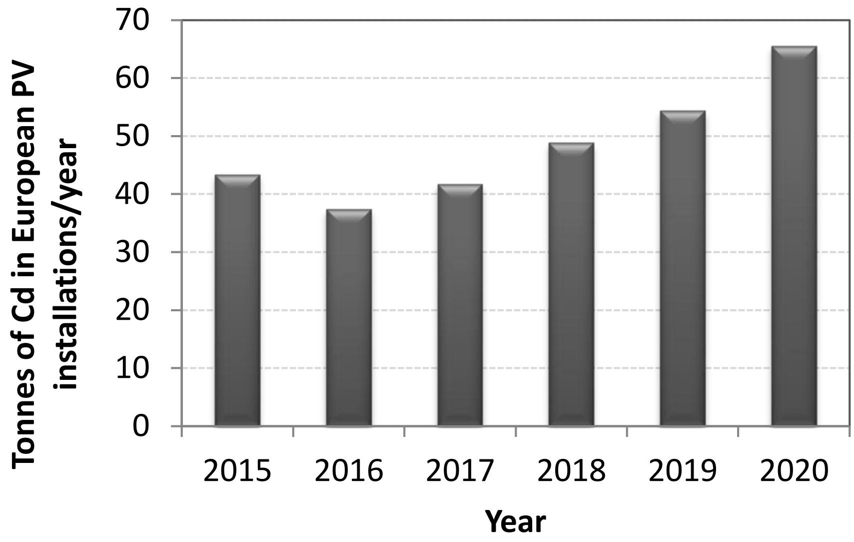


**Figure 49** Calculated Cd mass expected to be employed yearly in European CdTe PV installations.

As has been highlighted before, CdTe PV modules will provide a safe and almost fully recyclable temporary sequestration for this amount of Cd, and will contribute to mitigating the oversupply of raw Cd that is expected to happen in the future, due to the increasing demand of Zn. Also, this deployment of CdTe PV modules will displace conventional fossil fuel-based electricity generation, contributing in this way to curbing greenhouse gas emissions and heavy metal emissions.

According to the International Renewable Energy Agency, the amount of cumulative waste volumes of end-of-life PV panels in Europe will increase from 325,000 tonnes in 2020, to 1,970,000 tonnes in 2030 and 10,825,000 tonnes in 2050[111]. These figures correspond to the estimations assuming an “early-loss” scenario, which takes account “infant”, “mid-life” and “wear-out” failures that may occur before the end of the 30-year lifespan. Assuming a constant share in Europe over the years of 4% for the CdTe PV modules, and a recycling recovery rate for Cd of 90%, the amount of Cd recovered from recycling in the European Union has been calculated until 2050, and these data are shown in Figure 50. According to these estimations, the cumulative amount of Cd recovered from recycling activities will increase from almost 6 tonnes in 2020 to more than 120 tonnes in 2050.

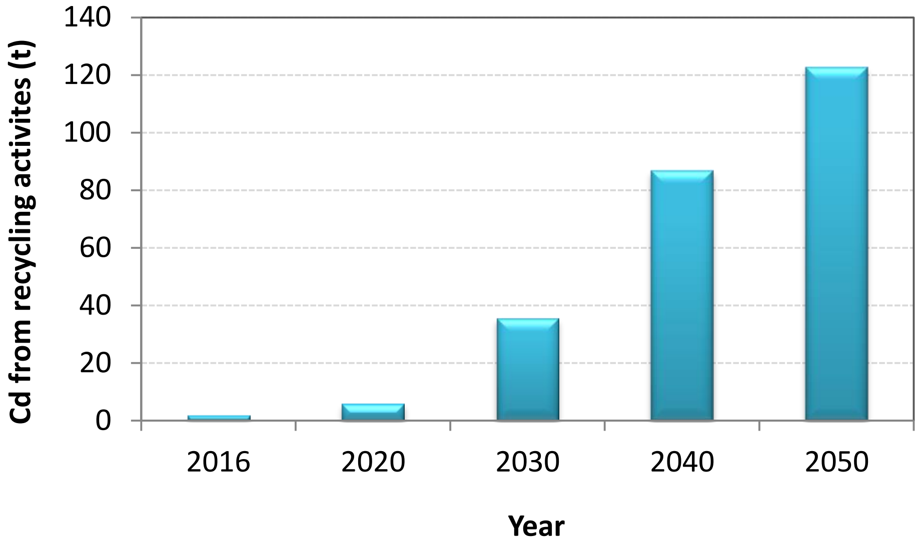


**Figure 50** Calculated cumulative Cd recovered from the recycling of CdTe PV modules in Europe.

The need for the recovery of valuable materials in the future, as well as the existing directives, such as the current WEEE for the recycling of electronic products, concur to indicate that CdTe PV modules will very likely be recycled after their decommissioning. The amount of Cd obtained from the recycling activities could be used again by the PV industry to manufacture PV modules, which will again provide a solution for the generation of clean electricity.

# 3.- CONCLUSIONS

The main conclusions extracted from the in-depth analysis of the documents reviewed in the report are summarized below, organized by the different aspects.

***First Solar's CdTe PV technology and cost roadmaps***

- ✓ First Solar's CdTe PV technology has shown a remarkable increase of 5% in cell efficiency in 5 years, reaching a value of 22.1% in 2015 that overpassed polycrystalline silicon record cell (21.3%) and which is very close to that of CIGS solar cells.
- ✓ Grading with CdSe at the front interface has been a key breakthrough in the recent evolution of First Solar's CdTe PV technology. It allows the photocurrent collection to reach an unpreceded level of spectral response with quantum efficiencies close to 90%, extending well towards the UV and the IR.
- ✓ At the module level, CdTe technology is the fastest growing technology in efficiency, which compares now to Si average high volume production efficiencies at about 16%.
- ✓ Routes for increasing the efficiency of First Solar's CdTe PV technology to about 24% exist, such as the increase of the open circuit voltage specifically. The work on single crystal and alternative deposition technologies, like CVD, is very useful for these prospects.
- ✓ On a given cumulative production, the price of CdTe modules is lower by a factor of 4 to 5 compared to silicon wafer based technology. Strictly reasoning with the mechanism of price reduction by scale effect, this means that CdTe technology is inherently cheaper than silicon technology, with the reason being the simpler production process of thin film technologies with less steps and the module produced at the same time of the cell.

***Performance aspects of First Solar's CdTe PV modules technology***

- ✓ First Solar's PV modules are produced according to state-of-the-art standards with respect to product lifetime, reliability, quality and performance. For this purpose an elaborate quality control and reliability testing program is maintained close to production. Quality control and accelerated laboratory testing is performed at ISO 17025 calibrated laboratory equipment for high volume production monitoring, technology development, product reliability and warranty issues.
- ✓ PV module reliability testing under outdoor conditions is available at various test sites representing different climatic conditions from arid to hot and humid. Specific climatic impact factors are evaluated with regard to First Solar's CdTe technology performance and energy yield. A profound understanding and engineering of module materials assure a stable and predictable field performance under typical European climate conditions.
- ✓ First Solar operates laboratories for advanced failure diagnostics and product development in order to employ a Failure Mode an Effects analysis (FMEA) for product innovation and development.

- ✓ Long-term field performance monitoring programs, with a time horizon of over 17 years, has led to an impressive amount of data and knowhow on manufacturing PV modules with extended lifetime and high energy yield. Critical environmental stress levels and degradation modes (e.g. PID, LID) have been thoroughly tested and mitigation strategies implemented.
- ✓ A particular benefit is drawn from First Solar's facilities in utility-scale PV power plant monitoring and performance analysis. A simultaneous evaluation of measured PV system output and modelling leads to a high accuracy in the predicted energy ratio (PER).
- ✓ First Solar is paying special attention to anti-soiling performance of its modules due to the high performance impact ranked at level 3 after insolation and temperature. Accordingly, a very detailed investigation of monitoring and system impact analysis is available with specific regard to First Solar's CdTe technology. Furthermore, evaluation of anti-soiling coatings and cleaning strategies and guidelines are available.
- ✓ First Solar is achieving highly innovative results in working at grid integration issues at PV power plant level. The implementation of PV plant control systems support grid stability as a whole through dynamic voltage and frequency regulation, active power management and ramp-rate control.

***EH&S aspects of First Solar's CdTe technology***

- ✓ First Solar's manufacturing facilities are equipped with the necessary technology to treat waste effluents from all manufacturing operations, including module recycling. Current Cd air emission and wastewater effluents are well below the local regulatory threshold limits. First Solar's Industrial Hygiene Management Program for Cd management includes air sampling for personal area and equipment, as well as medical surveillance for employees, including blood and urine testing. Cadmium levels in indoor air are well below the Occupational Exposure Limits. With regard to the bio-monitoring tests, Cd levels in blood and urine are demonstrated to be well below U.S. Occupational Health & Safety Administration criteria.
- ✓ Under normal operation, First Solar's CdTe PV modules do not pose any environmental or health risk, since no emission of hazardous materials occurs.
- ✓ In the event of a fire, utility scale PV power plants have limited on-site vegetation, with grass fires having short residence times and maximum temperatures below the melting point of CdTe. With regard to a rooftop fire event, more data has been found supporting the initial evidence that in case of a fire incident most of the Cd remains within the molten glass. For the public, the concentration of Cd found in the fumes was reported not to be dangerous. Because most of the Cd content is not being emitted to air and is remaining in the module and module debris, it was recommended to accordingly dispose the contaminated residues and replace the soil, which is a normal procedure following building fires. Water used to extinguish the fires was reported to contain similar quantities of Cd assumed in a prior fate and transport study which found insignificant impacts to soil and groundwater, where the

latter could be confirmed with soil analysis.

- ✓ Peer-reviewed fate and transport investigations regarding leaching of broken or defective CdTe PV modules confirm that the related potential risk is very low, based on worst-case modeling, experimental data, and O&M practices (routine inspections and power output monitoring) that detect and remove broken modules. Nevertheless, additional independent investigations, published in peer-reviewed scientific journals would contribute to support First Solar's experimental results. These scientific studies should include both, broken modules representative of field exposures and modules with integrity issues resembling possible situations encountered towards the end of life. For example, independent broken module leaching studies have historically been conducted by Fraunhofer Institute in Germany and NEDO in Japan on older generation CdTe PV modules with results below health and environmental screening limits.
- ✓ The principal application of First Solar's CdTe PV modules is in large commercial and utility scale power plants, where grid codes and technical standards require handling of PV modules only by qualified and trained personnel. The risk of exposure or non-intended uses is therefore limited by the nature of the product and installations. The disposal of CdTe PV modules in uncontrolled landfills has been studied through actual landfill compacting tests and fate and transport analysis. The results suggest that the health risk associated with the disposal of CdTe PV modules in uncontrolled landfills is minimal at the present usage rates. More specifically, the screening level cumulative non-carcinogenic hazard index could exceed 1.0 only if the annual waste volume amounted to over 14 million modules over 20 years or over 5 million modules in 1 year into a single unlined landfill. Although high-value recycling (recovery of glass and semiconductor materials) is the ideal option for the end-of-life of PV modules, including CdTe PV, it must be entrusted to companies with the required knowledge and best environmental, health and safety practices, such as those being documented by CENELEC in support of the WEEE Directive (draft Standard EN50625-2-4). In the case of informal recycling, unlike household consumer electronics, there are few components in a monolithic thin film module to dismantle, aside from the junction box and cables.
- ✓ First Solar is leading the PV industry in the establishment of collection and recycling programs that ensure end-of-life recycling with a proven technology. In the EU, the inclusion of all PV technologies in the WEEE directive together with First Solar's recycling facility (in Frankfurt/Oder, Germany) ensures the proper systems and policies to sustainably implement CdTe PV technology. Outside of the EU, First Solar's recycling services are globally available and implemented with recycling facilities in Perrysburg, USA and Kulim, Malaysia, and adoption is based on competitive pricing.

***Life cycle impacts of the large –scale deployment of the CdTe PV technology***

- ✓ If CdTe PV technology were deployed to displace conventional fossil fuel-based electricity generation, the benefits in terms of reduced depletion of fossil-fuel resources and reduced greenhouse gas emissions would be between one and two orders of magnitude.

- ✓ Deploying CdTe PV in Europe would actually decrease the overall Cd emissions per unit of generated electricity, while providing a safe and almost fully recyclable temporary sequestration route for the oversupply of raw Cd that is expected in the future, due to the increasing demand for Zn (of which Cd is an unavoidable by-product). More specifically the overall Cd emissions from the full life cycle of CdTe PV technology were quantified at approximately 170 mg/GWh, of which more than 90% is caused by the use of fossil fuel electricity in the PV manufacturing processes. In comparison, life cycle Cd emissions from hard coal and oil electricity generation amount to 3.1 g/GWh and 43.3 g/GWh, respectively.

- ✓ In terms of total land transformation per unit of electricity, the performance of CdTe PV technology is several times better than that of other renewable technologies like wind, hydro and especially biomass, while it remains of the same order of magnitude as that of conventional technologies such as coal and nuclear power. A key difference with respect to the latter technologies, though, is that the type of land transformation caused by CdTe PV installations is much “lighter”, and leads to much easier ecological restoration after decommissioning.

- ✓ Other environmental benefits of CdTe PV technology comprise much reduced demand for water, when compared to alternative electricity generation technologies. This is especially important, since PV is likely to be preferentially deployed in the better-insolated areas of the world that are also typically more arid.

- ✓ When considering the large-scale deployment of CdTe PV, the only aspect of the life cycle environmental performance that has been identified to be a cause for some concern is the projected demand for copper, which is used in comparatively large quantities in the electrical part of the BoS and therefore is not unique to CdTe PV. However, in the long-term, this concern is likely to be mitigated by the growing supply of secondary Cu derived from end-of-life recycling of decommissioned PV systems.

- ✓ In view of all the points enumerated above, it may be concluded that from most points of view, the long-term effects of a future projected large-scale deployment of CdTe PV technology would be very positive for the environment.

# First Solar's CdTe module technology – performance, life cycle, health and safety impact assessment


Stellenbosch University

**Centre for Renewable and Sustainable Energy Studies**

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15 December 2015


CENTRE FOR RENEWABLE AND SUSTAINABLE ENERGY STUDIES

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| Project Dates | Start: 26 March 2015 | End: 31 July 2015 (Draft Report) | |
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| CRSES Project No | CRSES 2015/06 | Stellenbosch University No | S004157 |
| Brief project description | The objective is to provide First Solar with an independent review for using thin film cadmium telluride (CdTe) photovoltaic (PV) technology in the installation of future power plants in South Africa, based on scientific studies, the result of which is presented in this report. | | |
| Key findings | First Solar's CdTe thin film technology photovoltaic modules are a technically feasible, environmentally friendly and safe way to produce electricity in South Africa. | | |
| Keywords | First Solar, thin film, solar PV, photovoltaic, cadmium telluride | | |
| Approval | Project Lead: Dr. AJ Rix<br>Reviewer: Mr. U Terblanche<br>Director: Prof. JL van Niekerk | | |

# EXECUTIVE SUMMARY

Until 2011, the solar photovoltaic (PV) industry in South Africa consisted of small-scale installations, predominantly off-grid and in rural areas. In 2013, construction began on utility scale PV projects with a combined capacity of 632 MW and since then, a further 1 267 MW of utility scale PV projects have been awarded, with an approximate total of 1 000 MW of these utility scale PV that is already connected to the national grid. These projects were the result of the Department of Energy's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP). When compared to the well-developed solar PV market in Europe, South Africa is still at a very early stage with the prediction that the PV market is expected to grow rapidly over the next years.

The electricity supplied to the South African grid is predominantly (90%) generated from coal. With this source of power well established in South Africa, the life cycle cost of established coal-fire generated electricity is low. However in 2013 the utility scale PV market reached grid parity with new-build coal power generation options, and in 2014 the 1 000 MW of connected utility scale PV power plants resulted in a nett benefit of R 800 million to the South African economy.

South Africa has an excellent solar energy resource with the warmest days from December to February when temperatures can exceed 40$^{o}$C in some parts of the country. The First Solar CdTe modules are less affected by high temperatures than the average crystalline-Si module and this characteristic has recently been proven for locations in South Africa by the ARUP consulting engineer group (ARUP, 2015).

Today, First Solar is producing CdTe modules with 16% efficiency and a manufacturing cost below USD $0.46/Watt. Furthermore, First Solar recently announced that they have produced a thin film PV module with full area efficiency of 18.2%. First Solar has test programmes and quality management systems in place to ensure their modules comply with the required qualification standards.

During a site visit to First Solar's Perrysburg (USA) facility, the safety, industrial hygiene and occupational health procedures that are in place throughout the facility were witnessed and discussed. First Solar has proven that their workplace is safe, even to workers with a high risk of potential exposure to cadmium compounds.

Independent toxicity studies by (Zayed & Philippe, 2009) indicate that cadmium is more toxic in the elemental form compared to the relatively stable CdTe compound and that the acute inhalation and oral toxicities of CdTe in rats are found to be at least 8.9 times lower than that of elemental cadmium.

Raw material, manufacturing, operation and decommissioning stages of CdTe cells typically produce two orders of magnitude less cadmium emissions to the environment compared to coal-burning power plants. The solid semiconductor compound CdTe is a crystalline, non-flammable powder, practically insoluble in water and with a melting point above the typical temperature reached in veld fires. (Fthenakis, et al., 2005) has shown that 99.96% of the cadmium is retained in the molten glass when exposed to extreme temperatures. Other sources that contribute to the exposure of cadmium to humans include coal-burning power plants that emit significant amounts of cadmium into the environment and even more significantly, the use of phosphate fertilisers. Under normal conditions, the CdTe and CdS (cadmium sulphide) compounds are fully encapsulated between two sheets of glass and are, therefore, unlikely to breakdown chemically. Encapsulating cadmium as CdTe in PV modules presents an alternative, safer option for cadmium use when compared to most of its other current uses.

The possible benefits of replacing coal-intensive electricity from South Africa's grid with ground-mounted CdTe and roof-mounted Si PV systems was investigated and the results showed that such a replacement would yield a reduction in the various life cycle impact categories. CdTe modules have the least amount of harmful air emissions and have the lowest carbon footprint compared to CIGS and cost-competitive multi-Si systems. No literature was found indicating that CdTe modules pose a significant environmental and/or health threat due to cadmium emissions or exposure.

Another concern associated with thin-film PV modules is the availability of materials used in the semiconductor layer. Efficiency improvements of CdTe technology, that result in using less CdTe material, may have such a great impact that the 'primary' demand for tellurium could decline after 2020 regardless of increased CdTe market growth.

The life cycle land transformation of ground-mounted PV technologies in general is comparable to that of coal and natural gas cycles. As solar power plants do not require mining for fuel during their lifespan, the land occupation impact of solar power plants decreases as the power plant lifespan increases. PV systems have the potential to be constructed, operated and decommissioned in ways that avoid excessive impact on land and habitats.

Recycling is the most sustainable manner in which modules can be handled at the end of their useful life, not only from an environmental impact perspective but also in terms of resource efficiency. Literature recommends that the use of cadmium as a toxic element is recycled, despite cost implications, and that tellurium recovery is seen as an additional benefit. Environmentally sensitive metals, such as Pb, Cd, In, Ga, Se, Te, Cu and Ag, are common in the industry and therefore recycling is important for all PV technologies. With currently over 177 GW of PV installed worldwide, recycling is crucial to managing large, future PV waste volumes and to reclaiming valuable materials.

Following the visit to the recycling plant at the Perrysburg site and the related discussions, it is clear that the recyclability is fully integrated in the module design. In terms of the current process recycling technology, over 90% of the semiconductor and 90% of the glass material is recycled for beneficial reuse. Looking to the future, regulatory frameworks, greater experience and rising disposal costs will likely lead to smaller and more mobile recycling facilities, with the operational costs of such facilities expected to fall below hazardous waste disposal costs.

Water consumption for the full life cycle of thermoelectric (e.g. coal and nuclear) power plants is substantial. This is especially relevant in water scarce countries like South Africa, where dry cooling has become mandatory and has the potential to reduce the amount of water withdrawn for this purpose to some extent. In this regard, total life cycle water withdrawal per MWh is third lowest for PV (wind power and hydropower are lower). Silicon-based PV has a higher life cycle water consumption level than CdTe due to the water needed for high-purity silicon production. In terms of waste treatment, only the water used in the manufacturing process contains trace amounts of cadmium and all First Solar factories are equipped with state-of-art waste water treatment and analytical capabilities for 24/7 in-house water testing to inform operators if a batch of waste water can be discharged after treatment.

First Solar's CdTe thin film technology modules are a technically feasible, environmentally friendly and safe way to produce electricity in South Africa.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| BOS | Balance of System |
| CdTe | Cadmium Telluride |
| CMS | Change Management System |
| CRSES | Centre for Renewable and Sustainable Energy Studies |
| CSIR | Council for Scientific and Industrial Research |
| CSP | Concentrated Solar Power |
| DRAS | Delisting Risk Assessment Software |
| ECHA | European Chemicals Agency |
| EOL | End of Life |
| EPA | Environmental Protection Agency |
| EPBT | Energy Payback Time |
| EU | European Union |
| EVA | Ethylene-Vinyl Acetate |
| GHG | Greenhouse Gas |
| GHI | Global Horizontal Irradiance |
| GHS | Globally Harmonized System of Classification and Labelling of Chemicals |
| IEEE | Institute of Electrical and Electronics Engineers |
| LCA | Life Cycle Assessment |
| PERC | Passivated Emitter Rear Cell |
| PID | Potential Induced Degradation |
| PV | Photovoltaic |
| REIPPPP | Renewable Energy Independent Power Producers Procurement Programme |
| R&D | Research and Development |
| SHE | Safety, Health and Environment |
| TCLP | Toxicity Characteristic Leachate Procedure |
| USA | United States of America |
| USM | Unrefined Semiconductor Material |
| WEEE | Waste Electrical & Electronic Equipment |

# Introduction

### *Purpose and scope*

Since 2003, First Solar has invited specialists from various countries and regions to carry out 13 literature reviews on their cadmium telluride (CdTe) module technology. The specialists who participated in these reviews were from the USA, the European Union (EU), France , Spain , Japan , Germany, Italy, India, Thailand, the Middle East, China, Chile and Brazil.

In 2015, First Solar approached the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University to conduct a similar peer review based on thin film photovoltaic (PV) literature and to visit one of First Solar's manufacturing facilities. The proposed peer review would include a South African based assessment of specific performance, health and safety throughout the product life and the life cycle impacts that large-scale deployment of CdTe PV systems would have on the environment.

This report focuses on the South African utility scale PV market and describes First Solar's CdTe PV module technology comparing it to other commercially available PV technologies. The literature review provides comment on the chemistry and toxicology, raw material sourcing, manufacturing, product use, end-of-life disposal, as well as the overall life cycle impacts on the environment, public health and public safety, and considers other energy alternatives.

### *The South African utility scale PV market*

Until 2011, the solar photovoltaic (PV) industry in South Africa consisted of small-scale installations, predominantly off-grid and in rural areas. In 2013, construction began on the first utility scale PV projects with a combined capacity of 632 MW. These projects were the result of the Department of Energy's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP). A further 1 267 MW of utility scale PV projects have since been awarded through the REIPPPP, on which construction has started with an approximate total of 1 000 MW already connected to the national grid. Compared to the well-developed solar PV market in Europe, South Africa is still at a very early stage but the PV market is expected to grow rapidly over the next year as can be seen in Figure 1, courtesy of the Council for Scientific and Industrial Research (CSIR) (Bischof-Niemz, 2015).

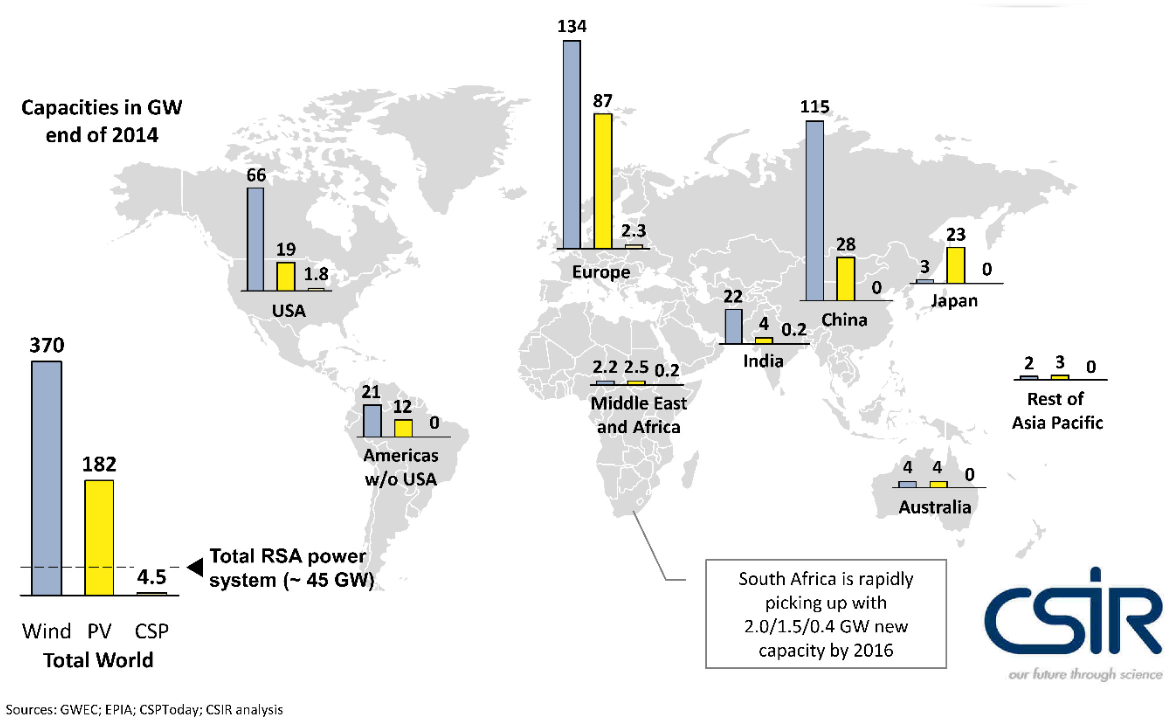


**Figure 1. Renewable energy capacity at the end of 2014 (Bischof-Niemz, 2015)**

South Africa is supplied with electricity generated mainly from coal, due to the abundant availability of the resource locally and the low cost of generation from older, existing coal-fired power plants, but in 2013, the utility scale PV market reached pricing that makes this a cost competitive power generator, because of the competitive tender REIPPPP. The resulting cost for wind, PV and concentrated solar power (CSP) of the four bid windows in the REIPPPP is shown in Figure 2 (Bischof-Niemz, 2015) where the cost of utility scale wind and PV is now below the cost of new-build coal or gas options. In 2014, the approximate 1 000 MW of utility scale PV power plants connected to the South African grid produced 1.12 TWh of the approximately 250 TWh required, and according to a recent study done by the CSIR, renewables resulted in a nett benefit of R 800 million to the South African economy (Bischof-Niemz, 2015).

On 16 April 2015, South Africa's Minister of Energy announced the expansion and acceleration of the REIPPPP wherein a further 1 800 MW of renewable energy, which includes PV, will be procured, and the minister will submit a new determination for an additional 6 300 MW of renewable energy for the approval of the energy regulator.

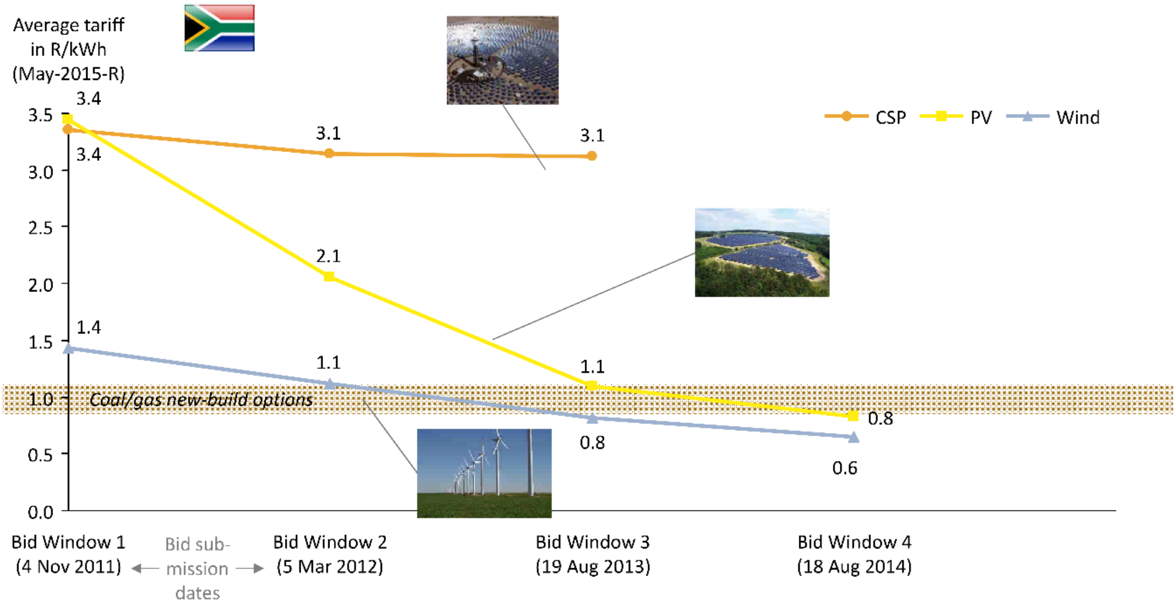


**Figure 2. Four bid windows' results of Department of Energy's REIPPPP (Bischof-Niemz, 2015)**

The small-scale PV market in South Africa is growing, although at an unknown rate. The known installations amount to approximately 44 MW as of 21 June 2015 (Anon., n.d.) and it is likely that there are an unknown number of small-scale installations that are, therefore, not represented in the 44 MW.

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# 1: Region-specific performance aspects

The aim of this section is to evaluate the region-specific performance aspects of First Solar's thin film CdTe technology and specifically, the technology roadmap, the influence of climate, reliability testing, grid integration and the field performance data of modules.

## 1.1: First Solar's CdTe thin-film PV technology

First Solar, founded in 1999, is the first company to break through the $1/watt manufacturing cost barrier and implement a global PV module-recycling program. According to First Solar's manufacturing cost forecast of 2013 for CdTe PV modules (de Jong, 2013), First Solar is aiming to produce modules for less than $0.40/watt in 2017. At the 2015 IEEE PVSC conference, (Garabedian, 2015) from First Solar indicated that their actual 2015 manufacturing cost is below the 2013 forecast of $0.43-0.46/watt for 2015.

First Solar held various world records regarding the best research-cell efficiencies for thin-film technology (Figure 3 shows the CdTe cell records in green circles with yellow centres (NREL, n.d.)). The R&D efforts of First Solar have been paying off since 2013, with cell efficiencies of up to 21.5%, surpassing the Trina Solar multi-crystalline-Si cell record of 20.8%. At the 2015 Institute of Electrical and Electronics Engineers (IEEE) PV specialist conference in New Orleans, First Solar announced that they have produced a prototype thin film PV module with full area efficiency of 18.2%, thereby also surpassing the 17.7% full area efficiency of the Trina Solar 324.5 W multi-crystalline passivated emitter rear cell (PERC) module (Garabedian, 2015).

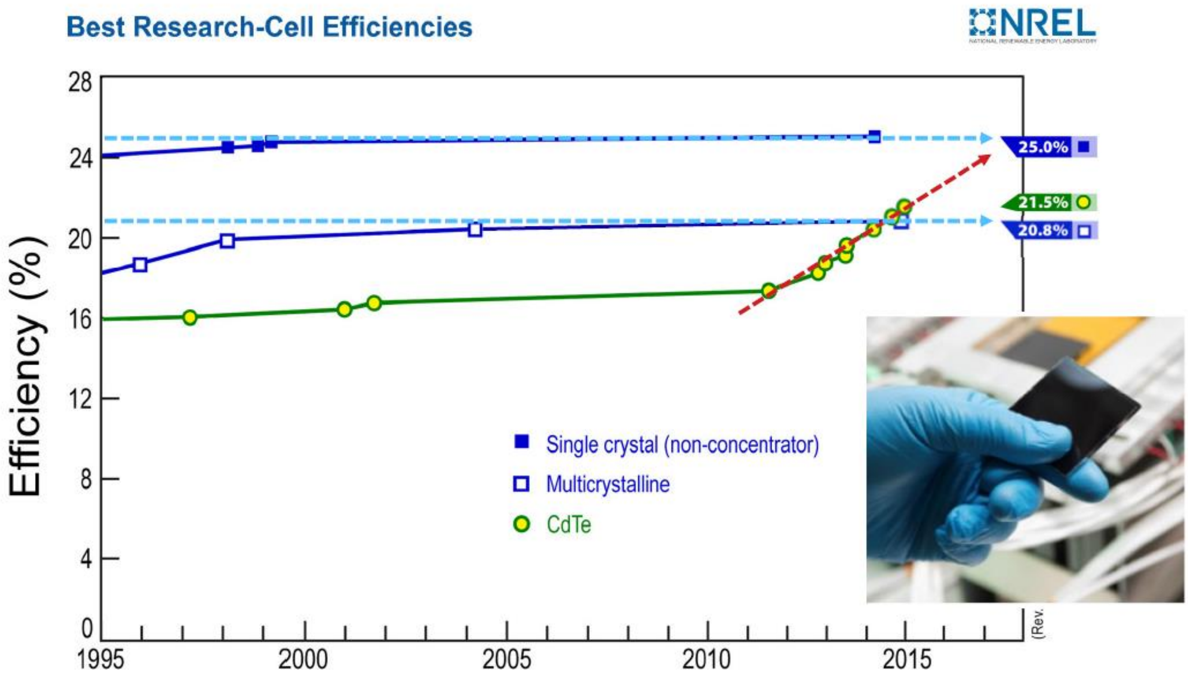


**Figure 3. The National Renewable Energy Laboratory's solar cell efficiency chart showing the evolution of the single crystal, multi-crystalline and CdTe technologies**

First Solar has a long-term goal to reach 24.8% research cell efficiency by increasing the open circuit voltage, the fill factor, and the current density of their cells, thereby moving towards the 25% efficiency of the record-holding mono-crystalline cells produced by SunPower (NREL, n.d.). The 2017 goal for First Solar is to commercially manufacture a module with an efficiency of 19.5% (Garabedian, 2014).

The First Solar series 4 PV module has a 25-year warranty and is compatible with 1 500 V plant architectures whilst remaining potential induced degradation (PID)-free. The modules have received various IEC certifications, comply with ISO 9001 and ISO 14001 and have a class B fire rating (Class A Spread of Flame) according to UL and ULC 1703 standards.

## 1.2: Factors influencing PV module performance

Many factors influence the performance of PV systems, with those most often considered being the global horizontal irradiance (GHI) and the ambient temperature of a site. South Africa has an excellent solar resource, as shown in Figure 4 and a wide variety of climates. The coldest days are from June to August and the warmest days from December to February, when temperatures can exceed 40 °C in some regions.

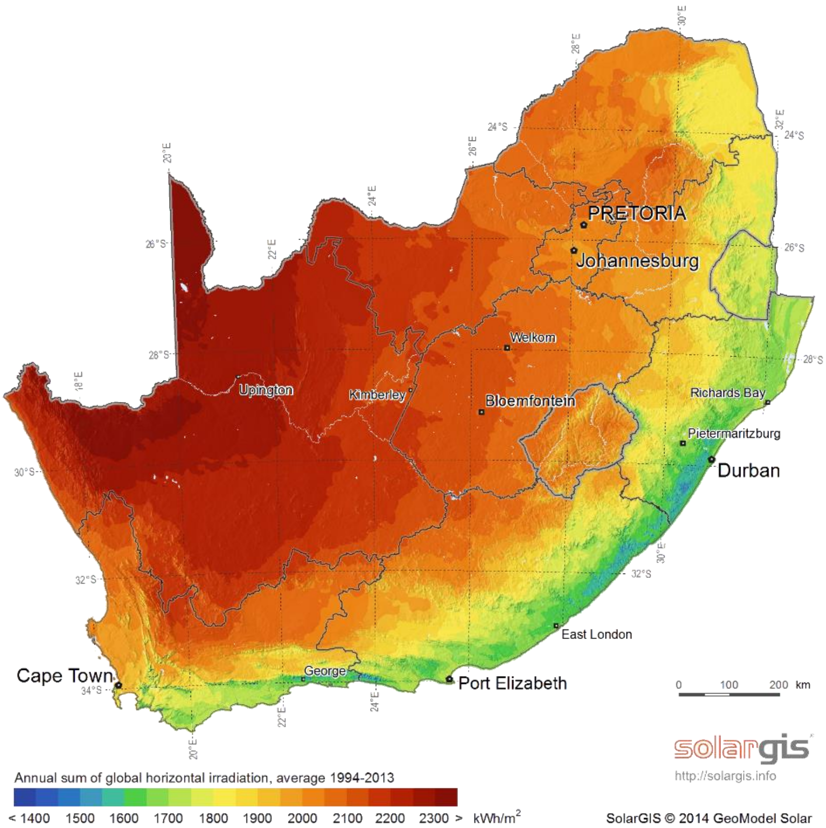


**Figure 4. GHI map for South Africa (GeoSun, n.d.)**

High temperatures negatively influence the power generation capability of PV modules including First Solar CdTe modules. The First Solar CdTe modules are, however, less affected by high temperature than the average multi-crystalline-Si module, as shown in Figure 5 (Strevel, et al., 2012). In the regions in South Africa that experience the warmest climates, the thin film modules would yield more energy than multi-crystalline modules.

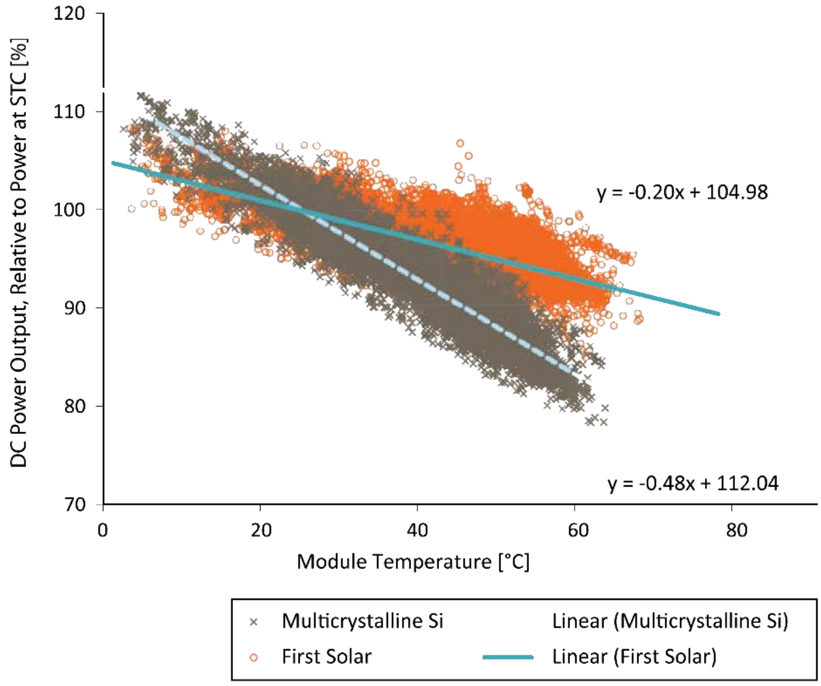


**Figure 5. First Solar and multi-crystalline DC power output vs temperature (Strevel, et al., 2012)**

The solar spectral irradiance distribution describes light intensity as a function of wavelength. The reference spectral irradiance distribution under which PV module nameplate ratings are defined is given by ASTM G173 and shown in Figure 6. A PV cell can only use a certain portion of the light spectrum as shown by the quantum efficiency curve for a CdTe cell, in Figure 6 (Lee, et al., 2015; Nelson & Panchula, 2013). Because the First Solar cells have a narrow wavelength band that exhibits high efficiency and this band excludes the 950 nm wavelength affected by the amount of water vapour in atmosphere, the energy available to a First Solar PV cell would thus be less affected by high humidity conditions. Figure 7 shows the spectral response characteristics of different PV technologies and here, the effect of humidity can be seen at around 950 nm where the CdTe technology has a low spectral efficiency and the c-Si module has a high spectral efficiency (AUO, n.d.). Thus, if you compare the performance of a First Solar CdTe module with a c-Si model in very humid conditions (such as in the city of Durban), the CdTe module would have a higher output power.

First Solar appointed ARUP consulting engineers to conduct an independent module comparison, by simulation, for First Solar's CdTe modules with single- and multi-crystalline modules at Vryburg, Upington and Bloemfontein in South Africa. The report revealed that for a plant with the same nameplate capacity, the CdTe modules produce a higher annual yield (ARUP, 2015). The ARUP report also shows the effect on the annual yield due to the influence of humidity or spectral shift and that the modules can have an increased output when true-tracking is employed instead of backtracking[1].

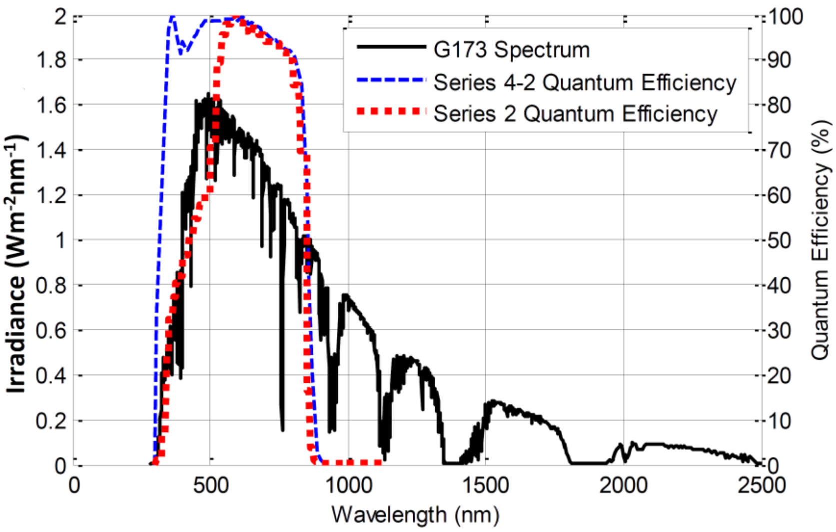


**Figure 6. QE curves for First Solar Series 2 and Series 4-2 modules and spectrum as defined by G173 standard (Nelson & Panchula, 2013)**

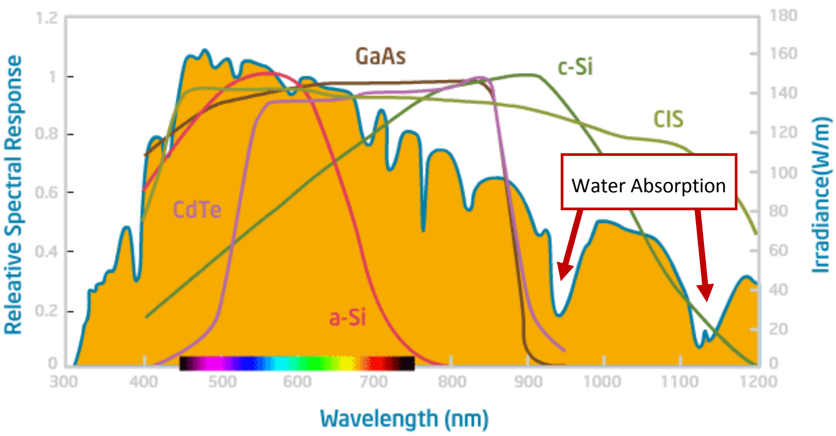


**Figure 7. Spectral response characteristics of different solar module technologies and the irradiance from the sun (AUO, n.d.)**

[1] True-tracking is when solar modules are tilted to follow the sun regardless of inter-row shading. Backtracking is when the inter-row shading begin and the tracking angle stop following the sun but returns to a zero shading position in order to reduce near shading caused by adjacent PV modules.

Apart from temperature and precipitable water, soiling can also influence a PV power plant's performance. In South Africa, the majority of utility scale power plants are installed in more arid regions where dust may negatively influence the power generation capabilities of these plants. A recommendation is that soiling measurement equipment is installed as a standard to monitor the performance of a plant. First Solar has done extensive soiling tests and confirms that when their modules are used for soiling measurements the short circuit currents can be used, which serve as a proxy for the effective irradiance received by the soiled versus the clean module (Gostein, et al., 2014).

## 1.3: Reliability, grid integration and filed performance

First Solar has a test programme and quality management system to make sure their modules comply with the required qualification standards. Modules are sampled from the production line and approximately 80 000 modules per annum (roughly 8.0 MW) undergo various tests at the First Solar indoor reliability labs (Experts, 2015; First Solar (P. Buehler), 2015). Apart from the indoor testing, First Solar also carries out outdoor testing at various tests sites to verify and validate the indoor laboratory results. Through the development process, First Solar improved their modules by changing the edge sealant to the proprietary 'Black' edge sealant that enhances the long-term durability and extended test performance of the modules. In the series 3 Black plus modules, the back contact composition was also changed to minimise long-term degradation (Strevel, et al., 2013). According to observations during the site visit to the Perrysburg manufacturing facility, and the quality and reliability presentation at the recent 42$^{nd}$ IEEE PV Specialist Conference, the most recent First Solar series 4 version 2 modules have passed various long-term durability tests including the Thresher, Long Term Sequential, and Atlas 25+ tests (First Solar (P. Buehler), 2015).

Photovoltaic power plants are expected to operate for at least a 20-year period in South Africa and although long-term reliability is important, the integration with and the stability of the electrical network, or utility grid, is even more important. PV power plants operating in South Africa need to comply with the South African Grid Code. Grid integration is possible with the use of a plant controller that can control the behaviour of the plant accordingly to satisfy the specified requirement, standard or regulation (Morjaria, et al., 2014).

The field performance of the First Solar CdTe modules are being documented (Strevel, et al., 2012; Strevel, et al., 2013; Panchula, et al., 2011) and this also assists plant operators to improve their yield forecasting capabilities for CdTe modules, which is shown in (Strevel, et al., 2012; Strevel, et al., 2013) and here the measured plant performance is close to 100% of the P50 prediction.

# 2: Health and safety impacts of the CdTe

The aim of this section is to evaluate the safety, health and environmental (SHE) aspects associated with the production, testing and on-site implementation/operation of the First Solar CdTe modules. This evaluation was done over the life cycle of the module and is based on existing literature and site visit. During a site visit to First Solar's Perrysburg facility, the existing safety, industrial hygiene and occupational health procedures were observed and discussed (Experts, 2015). First Solar is OHSAS 18001 compliant with a safety first policy and implements industrial hygiene procedures that, through medical monitoring, have proven that the workplace is safe, even to workers with a potential high exposure risk to cadmium compounds.

## 2.1: CdTe stability and toxicity (catastrophic events)

In accordance with the classification from the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), adopted in 2015 by the European Chemicals Agency (no classification for CdTe in South Africa could be found), CdTe is classified as

i) harmful if inhaled;

ii) harmful to aquatic life with long lasting effects.

However, even in a worst-case rooftop fire scenario where there are 1 000 $m^2$ of CdTe modules with an average Cd content of 66 $g/m^2$ and a heat source of 60 MW, potential Cd emissions are still substantially below human health evaluation levels (Beckmann & Mennenga, 2011), actual Cd content in First Solar PV modules (Sinha, et al., 2012) is lower by an order of magnitude than that assumed by (Beckmann & Mennenga, 2011).

Independent toxicity studies indicate that Cd is more toxic in the elemental form compared to the relatively stable CdTe compound. For example, (Zayed & Philippe, 2009) studied the acute inhalation and oral toxicities of CdTe in rats and found the median lethal concentration and dose to be at least 8.9 times higher than that of elemental Cd. The CdTe compound also exhibits low aquatic toxicity (Agh, 2011; Kaczmar, 2011), no mutagenicity in bacteria (Agh, 2010; Kaczmar, 2011) and no acute adverse reproductive effects in rats (Kaczmar, 2011; Chapin, et al., 1994).

CdTe modules do not generate any toxic gases during normal operation. This is because the energy absorbed from the high frequency photons of the electromagnetic spectrum is not enough to break the bonding electrons in the solid lattice structure. The energy of any photon in the solar spectrum is therefore lower than the chemical bonding energy in the CdTe or CdS layers of a PV cell; this is the intrinsic feature that stabilises the Cd-containing compounds (Bonnet & Meyers, 1998).

## 2.2: Raw material sourcing

It is important to note that conventional silicon PV cells, as well as the coal used in coal burning power plants contain Cd. In fact, as highlighted in the life cycle study of (Fthenakis, 2004), raw material, manufacturing, operation, and decommissioning stages of CdTe cells typically produce two orders of magnitude less Cd emissions to the environment compared to coal burning power plants. That is to say, air emissions of 0.02 g Cd/GWh from CdTe PV cells, compared to 2 g Cd/GWh produced from coal burning power plants.

The main potential for harm to animals, humans or the environment relates to toxic gas emissions during catastrophic events, such as fires. Telluride is a rare metal, whilst Cd is a heavy metal and studies on the toxicity of Te in its elemental form show that it appears to be only mildly toxic and not carcinogenic (Raugei, et al., 2012).

The solid semiconductor compound CdTe is a crystalline non-flammable powder, practically insoluble in water and has a high melting point of 1 041°C. This melting point is above the typical temperature (800-1 000°C) reached in a veld fire (Martell, 2009), as opposed to the melting point of Cd metal of only 321°C (Lide, 2004). Testing has shown that 99.96% of the Cd is retained in the molten glass during fire testing up to 1 100°C (Fthenakis, et al., 2005).

## 2.3: Cadmium exposure during manufacturing

First Solar enforces proactive cadmium-containing material management practices that prevent the environmental exposure and human health risks associated with cadmium materials processing during module manufacturing. First Solar has an active medical monitoring programme for their employees to ensure that their industrial hygiene practices are effective. Medical monitoring results compare recently hired to long-term employees and smokers (cadmium is a constituent of cigarette smoke) showing that cadmium levels in workers are well below the threshold level and do not rise due to working in the manufacturing plant (Bohland & Smigielski, 2000). Table 1 lists other sources that can result in cadmium exposure (Van Assche, 1998).

**Table 1. Sources and relative contributions of Cd exposure to humans (in Europe) (Van Assche, 1998)**

| Cd source | Relative exposure contribution |
|---|---|
| Phosphate fertilisers | 41.3% |
| Fossil fuel combustion | 22.0% |
| Iron and steel production | 16.7% |
| Natural sources | 8.0% |
| Non-ferrous metals | 6.3% |
| Cement production | 2.5% |
| Cd products | 2.5% |
| Incineration | 1.0% |

## 2.4: Impact of CdTe PV on human, animal and plant life during operation

A typical Life Cycle Assessment (LCA) analyses the impact of material and energy flows in and out of a product. In evaluating the potential risk to the environment and the potential impact on human, animal and plant life, the CdTe PV manufacturing process and its commercial deployment should be viewed in the context of the Cd emission contributions from other industries. Vast quantities of Cd are released into the environment via primary fossil fuels industries (Fthenakis, 2004), whereas the CdTe PV industry utilises the by- or waste-products from essentially two base metal industries, i.e. Te from the copper (Cu) and Cd from the zinc (Zn) refiners. Neither Te nor Cd are found alone in commercial deposits.

Cd is generated primarily as a residue during electrolytic (hydrometallurgical) Zn production and as fumes and dust collected from emissions during pyro metallurgical processing. It is used primarily in NiCd rechargeable batteries, within paint pigments, plastic stabilisers and other uses making up the difference. Owing to the very large quantities of Zn metal produced, there are substantial amounts of Cd generated as by-product. If the market does not absorb the Cd generated, it is stored or disposed of as hazardous waste. Therefore, in light of the discussions in the previous section, encapsulating Cd as CdTe in PV modules presents an alternative and safer usage of the mineral compared to most of its current uses (Fthenakis, 2004).

## 2.5: Release of Cd from CdTe PV modules to the environment

Unless a strong oxidant such as hydrogen peroxide ($H_2O_2$) solution, used for leaching semiconductor material from PV modules during recycling, finds its way through cracks in a broken glass panel, no Cd (or Te) will be released into the environment because under normal conditions, the CdTe and CdS compounds are fully encapsulated between two sheets of glass.

An unlikely, albeit necessary, scenario to consider is the potential chemical release to an aquatic environment after decommissioning, i.e. if the PV modules end up in a landfill and toxic elements leach from the CdTe/CdS compound layers. Therefore, the aspect dealt with here relates to the disposal of large volumes of CdTe PV modules dumped in unlined landfills instead of being recycled or sent to an appropriate sanitary landfill. The standard Toxicity Characteristic Leachate Procedure (TCLP) is utilised by the U.S. Environmental Protection Agency (EPA) Delisting Risk Assessment Software (DRAS) risk assessment model to evaluate potential leaching risks using waste fragments less than 1 cm (Sinha, et al., 2014). Although end of life (EOL) module recycling and responsible disposal are important for all PV technologies, (Monier & Hestin, 2011) considered six different commonly used multi-crystalline silicon (c-Si) PV modules and found that the leachability of toxic lead (Pb) is significantly greater than that of Cd from CdTe PV modules. In fact, the potential negative impacts of improper disposal of c-Si PV modules have been found to be higher than for the CdTe PV module. Modelling that has been carried out by (Sinha, et al., 2012) shows that potential exposure to Cd, from rainwater leaching of broken modules, is highly unlikely to pose a potential health risk to humans.

The important question remains: what happens if large volumes of CdTe PV modules are sent to unlined landfills, e.g. if the unlikely scenario develops, where a large installation reaches an instantaneous EOL state and no recycling is enforced? The US EPA DRAS risk assessment model is utilised by (Sinha, et al., 2014) and concluded that such a scenario is unlikely to result in significant risk to human health and the environment. Furthermore, since the US EPA DRAS risk assessment model evaluates potential leaching risks using TCLP data for waste fragments less than 1 cm, it tends to overestimate the leaching potential of PV modules crushed by a landfill compactor, with 75% of the crushed module fragments typically larger than 1 cm and with some large pieces remaining intact (Sinha & Wade, 2015).

Besides using sanitary landfills, high value recycling will have the lowest environmental impact and will benefit resource recovery, provided this recycling is also conducted in an environmentally responsible manner.

# 3: Life cycle impacts of the large-scale deployment of CdTe PV systems

The overall life cycle impacts of large-scale CdTe deployment covers a broad spectrum and the following discussion includes comparisons with other technologies by using different life cycle analysis methods, the carbon footprint, metal depletion, land transformation, water usage and life cycle emissions of CdTe.

## 3.1: Carbon footprint, energy payback time and heavy metal emissions

By means of a hybrid life cycle assessment, (Bergesen, et al., 2014) investigates how the two most common thin film technologies (CdTe and CIGS) offer long term environmental benefits and how impacts from the technologies will potentially change between 2010 and 2030.

The review found that the life cycle impacts of thin-film PV technologies were at least 90% lower than other technologies in the U.S. generation grid mix across more than half of the impact categories in 2010. The life cycle greenhouse gas (GHG) emissions of CdTe and CIGS were estimated at 20 and 22 $gCO_2eq/kWh$ respectively, with much lower water depletion impacts and carcinogenic emissions than the U.S. grid. The metal depletion potential of thin-film technologies are regularly questioned and it was found that the metal depletion was estimated at 2.8 and 3.3 times higher than the U.S. electricity generation grid mix for CdTe and CIGS respectively in 2010, the metal depletion potential is not unique to only thin film but PV in general. However, by assuming that technology design and efficiency improvements will take place by 2030, stress on metal resources will be somewhat reduced, but other balance-of-system (BOS) components also need to be recycled to reduce this impact further. The suggestion to include BOS components in recycling comes from the finding that although most studies focus on the metals used in semi-conductive layers, as copper is used in inverters, transformers, wiring and other BOS components, it had the greatest contribution to the metal depletion potential. It is estimated that if PV generates 2.7 per cent of the U.S.'s electricity in 2030 as predicted in the IEA Blue Map scenario, the amount of copper needed would be greater than half of the total refined copper within the U.S. in 2013. Recycling of BOS components is thus expected to result in major reduction of future copper depletion.

All other life cycle impacts are expected to be reduced by 2030 for both thin-film technologies, but the two most significant reductions are a 69% reduction in life cycle $gCO_2eq/kWh$ emissions, and an expected 50% reduction in carcinogenic human health impacts with carcinogenic impacts primarily attributed to emissions from production of copper used for transformers, inverters, and wiring (Bergesen, et al., 2014).

Using methods developed by the Joint Research Center of the European Commission through the International Reference Life Cycle Data System, (Sinha, et al., 2014) investigated the possible benefits of replacing coal-intensive electricity from South Africa's grid with ground-mounted CdTe- and roof-mounted Si PV systems. The results showed that such a replacement would yield a reduction of more than 66% in various impact categories such as ecosystems, human health and natural resources. Furthermore, this reduction holds strong even with local content requirements such as in the Renewable Energy Independent Power Producers Procurement Programme where the balance-of-system would make up the bulk of this local content in CdTe systems. The only category without any perceived benefit was the mineral, fossil and renewable resource depletion category, within which recycling of all materials offers great potential for mitigation.

In an earlier study by (Fthenakis, et al., 2008), it was also found that although there are differences between the emissions per PV technology, these amounts are still much lower than that of conventional energy technologies, as shown in Figure 8. The same study confirmed that CdTe had the lowest amount of harmful air emissions because of the lower energy-intensive production processes required. Furthermore, if electricity generated from central PV systems could replace conventional grid electricity used to produce CdTe modules, harmful cadmium and other GHG emissions could be reduced by a minimum of 89%. The concept of increasing the 'quality' of energy used for PV production by using electricity produced by PV systems is termed a 'PV breeder'.

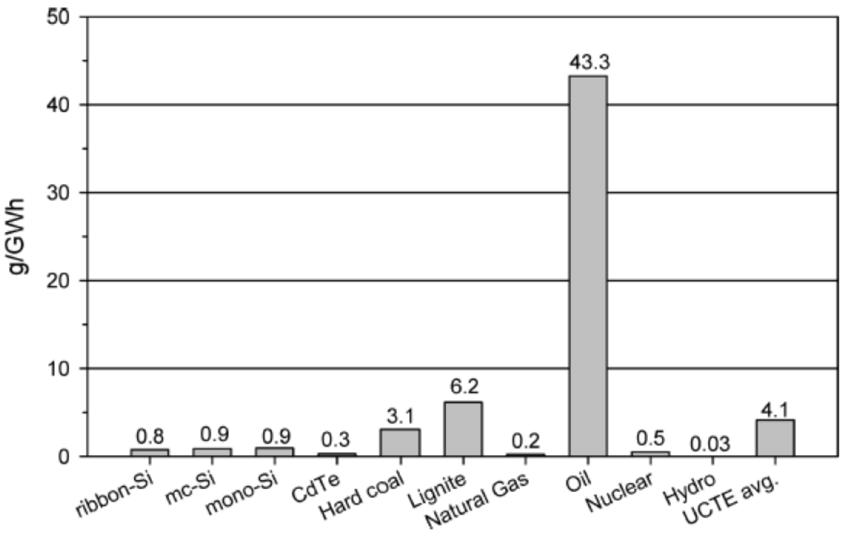


**Figure 8. Life cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalised for a Southern Europe average insolation of 1 700 kWh/m$^2$/yr, performance ratio of 0.8, and lifetime of 30 yrs (Fthenakis, et al., 2008).**

To determine the 'eco-efficiency' of different electricity generation technologies, seven potential impacts on the environment were combined into an 'eco-index'. In a report investigating this parameter, it was also found that differences between PV technologies are very small and on average have an environmental impact 10 to 20 times less than that of fossil electricity sources. The environmental impact of the BOS of different PV technologies was investigated and for ground-mounted systems, the BOS contributed 86% (CdTe) and 68% (silicon) of the environmental impact (Seitz, et al., 2013).

When investigating the GHG emissions of various commercial PV systems, CdTe production was found to have the lowest carbon footprint, at 15.83 $gCO_2eq$/kWh compared to 21.44 $gCO_2eq$/kWh for CIGS and 27.20 $gCO_2eq$/kWh for cost-competitive multi-Si systems. In addition to life cycle $gCO_2eq$/kWh emissions, energy payback time (EPBT) is another widely used concept to investigate the environmental performance of a technology or product. The associated energy payback times of the various PV technologies were also estimated at 0.68, 1.01 and 1.23 years for CdTe, CIGS and Multi-Si systems respectively. All values were estimated based on an annual irradiance of 1 700 kWh/m$^2$. The energy intensive nature of silicon purification and ingot growing is the primary reason for the higher carbon footprint and energy payback period associated with crystalline silicon PV technologies as shown in Figure 9 (de Wild-Scholten, 2013). In South Africa the annual irradiance is higher than 1 700 kWh/m2 and therefore the energy payback period will be shorter for the different PV technologies.

The results above are comparable to the results of another study that compared sustainability of the five most common PV systems (i.e. Mono-SI, multi-Si, a-Si, CdTe and CIGS). Here, CdTe was also found to have the lowest life cycle GHG emissions and EPBT. The combined emissions for the CdTe and CIGS thin-film technologies are in the range of 10.5-50 g$CO_2$eq/kWh and the combined EPBT was slightly higher than that of (de Wild-Scholten, 2013) ranging from 0.75-3.5 years. Mono-Si systems were found to have to highest energy requirements because of the energy intensive process of silicon purification and crystal growing (Peng, et al., 2013).

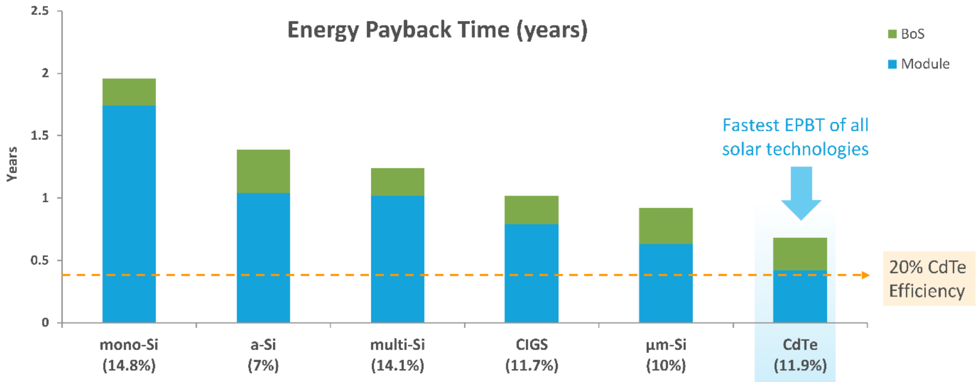


**Figure 9. Energy payback time for different PV technologies and their balance of system component (de Wild-Scholten, 2013)**

Taking into consideration other carbon sinks that are affected when land is cleared for the installation of a PV power plant such as carbon stocks and sequestration rates in various natural environments, carbon emission avoidance rates for solar and life cycle carbon emissions, (Turney & Fthenakis, 2011) found that solar power still has a net benefit in terms of life cycle emissions.

Cadmium release into the environment from CdTe modules is one of the main concerns related to the technology, however, several experiments have been performed by various authors where extremely conservative cadmium levels are regarded as threshold values, but no literature was found where it was shown that CdTe modules pose a significant environmental and/or health threat due to cadmium emissions or exposure. In a study where the impact of fire on encapsulated cadmium was tested, it was demonstrated that 99.5-99.96% of cadmium diffuse within the molten glass (Fthenakis, 2004). In terms of life cycle cadmium emissions, a typical U.S. coal-fired plant, with necessary cadmium removal filters, emits 2 g cadmium per GWh, whereas U.S. produced, CdTe modules emit 0.016 g cadmium per GWh, largely attributed to electricity use during PV module manufacturing. The results of the comparative benefits of thin-film PV technologies are well documented, but end-of-life risks associated with the modules remain a concern as policies and systems with regard to disposal or recycling appear to be inadequate in some instances (Fthenakis, 2012). In this regard, PV recycling under the EU WEEE Directive serves as an example of an effective policy instrument covering all PV technology end-of-life risks.

At a higher level, the contribution of CdTe to global cadmium flows, air- and water emissions have also been investigated. It was found that under a large growth scenario where 1 TW of CdTe is installed by 2050, cadmium emissions would still be an estimated two to three orders of magnitude lower than that of the 27 countries of the EU at the time of writing with those emissions largely attributed to electricity use during PV module manufacturing.. Although an increase in the use of cadmium is inevitable at higher installed CdTe capacity, the growth in this sector can very well reduce cadmium emissions and overall environmental pollution related to cadmium, globally (Raugei & Fthenakis, 2010).

## 3.2: Raw material availability

Another concern associated with thin-film PV modules is the availability of materials used in the semiconductor layer. The limiting element in CdTe modules is tellurium, where current production of this element is predominantly linked to base metal production and more specifically, anode slimes from copper electro-refining. Taking into account the estimated amount of annual tellurium production, cost limitations, tellurium recovery through recycling of CdTe modules and the expected increase in sourcing tellurium from recycled modules after 2045, upper production limits of CdTe modules are projected. The cumulated global production of CdTe from known tellurium resources is estimated at 120 GW by 2020, 0.9-1.8 TW by 2050 and 3.8-10 TW by 2100 (Fthenakis, 2012). These figures are closely related to the demand projections for copper and do not include the possibility of directly mining tellurium from ocean floor reserves where the element is present in ferromanganese nodules.

In another study that investigated three scenarios in terms of technological advancement and increase in recycling, it was found that efficiency improvements may have such a great impact that the 'primary' demand for tellurium could decline after 2020 regardless of increased CdTe market growth. However, estimates are influenced by demand projections for other uses of tellurium, and the current prediction is that the CdTe industry could be fully reliant on tellurium recovered from recycled modules by 2038 (Marwede & Reller, 2012).

(Houari, et al., 2013) uses a systems-dynamic model to determine whether the availability of tellurium will constrain the maximum potential growth of the CdTe market by 2050. The model showed that the most sensitive parameters regarding tellurium supply for reaching the maximum potential CdTe market are the use of tellurium during manufacturing and the increase of the recycling of modules, module lifetime, and the dynamics related to tellurium reserves. The study concluded that even without technology improvements or tellurium supply growth, the potential of the CdTe market is expected to be higher than previously estimated.

Calculating the amount of tellurium needed at different percentage CdTe market share, semiconductor layer thickness, and module efficiencies up until 2030, (Zweibel, 2010) also cannot foresee that tellurium would be a limiting factor within the next 20 years. These prospects excluded the possibility of increasing the tellurium reserve by improving and expanding metal refining processes or exploiting undersea tellurium resources.

From a combination of studies, it becomes evident that increases in CdTe module-efficiency and the reduction in semiconductor layer thickness will result in less CdTe used per module, and that the study of cadmium reserve quantities and the recycling of modules are key to improving the sustainability of the technology.

## 3.3: Land use and biodiversity

As land use intensity is often used as a proxy for various impacts, this aspect remains relevant when quantifying the impact of all electricity generation technologies. Land is becoming scarce in some areas for the specific purpose of solar power installations and competition might exist for other land use options; thus the efficiency of land use is becoming increasingly important (Hernandez, et al., 2014). It is often found that results in literature on the life cycle land use per electricity generation technology are contrasting because of the different approaches used to estimate land use, and whether or not both direct and indirect impacts are included. Direct impacts refer to the land where a power plant is located and indirect impacts refer to the land used for mining fuel for conventional electricity generation technologies. Life cycle land uses are also further grouped as land transformation, in area unit, per energy or land occupation where it is the land transformation, per year.

The life cycle land transformation of ground mounted PV technologies in general is comparable to that of coal and natural gas cycles, where different coal mining methods are applied and these values range between 100 – 500 $m^2$/GWh (Fthenakis & Kim, 2009). Land occupation is regarded as the more appropriate metric to use for comparison as more information is included in such figures over the lifetime of a power plant/technology. Since solar power plants do not require mining for fuel during their lifespan in the way that coal power plants do, the land occupation impact of solar power plants decreases as the power plant lifespan increases. In studies where the land impacts from mining as well as the recovery rate of mined areas are taken into account, the parity between coal and solar power plant land occupation is reached after 24 years (Turney & Fthenakis, 2011). It can further be argued that land occupation and transformation figures will continuously change as improvements are made with regard to the efficiency of modules.

The World Wide Fund for Nature took into account the energy demand of seven politically and demographically diverse regions with high solar resources and calculated the amount of land needed to supply 100% of each of these regions' electricity needs in 2050. In each of these regions, South Africa included, the amount of land needed for PV installations was less than one per cent of the region's total land area. The specifically required land use to produce 100% of South Africa's electricity in 2050, with solar PV, was calculated to be only 0.09% and equates to 1 130 $km^2$. Recognizing that 100% of electricity generation by PV is unlikely, this calculation demonstrates that the space needed on rooftops and on land is relatively small and would thus be far lower, at a lower percentage PV penetration (World Wildlife Fund, 2012). The impacts that will be caused by the transformation of this relatively small surface area can arguably also be managed by responsible land management practices such as proper site selection, minimizing soil grading and increased effort and caution concerning project decommissioning and module recycling. All of these recommendations have been made specifically for South Africa by (Sinha, et al., 2014).

Quantitative studies of the impacts of large solar power installations on plant and animal life are still relatively limited, as the technology on such a large scale is new when compared to older impacts such as mining and agriculture. The presence of wildlife is, however, important in determining a site for a solar power installation and certain areas may even be excluded due to the presence of wildlife (Woody, 2009). Impact on wildlife from solar power plants is largely determined by the land use of the installation as habitats are transformed and this is likely to have further impacts on animal movement and feeding. In situations where the ground preparation involves scraping of the soil surface bare earth is exposed, which may include the use of herbicide, bringing changes to the vegetation communities (Turney & Fthenakis, 2011). Another under-studied ecological impact of PV power plants is the microclimate change brought about through shading, and water runoff, from PV modules in the field.

By considering 32 possible impacts that may arise from large-scale solar power plants, (Turney & Fthenakis, 2011) concluded that solar power plants located in true deserts where wildlife is sparse or absent, are likely to have the least negative environmental impacts.

A study on the impact of solar parks on biodiversity in Germany reported that plant and animal life can be increased by following certain best-practice guidelines. These guidelines range from selecting and prioritizing site selection on specific land use types, to avoiding the creation of barriers that prohibit movement across a larger area, to regular maintenance and monitoring. This report did not focus on a specific PV technology, but remains applicable in the effort to reduce the environmental impact and increase the benefits from large CdTe ground-mounted installations.

The integration and management of environmental and energy systems is a field of study in which there is still plenty of room for learning and potential for synergies between these systems as well as that of climate protection and nature conservation (Peschel, 2010).

As the population grows and land becomes degraded and more scarce, it is essential that there must be parallel development between renewable energy and environmental protection. PV systems have the potential to be constructed, operated and decommissioned in ways that avoid excessive land and habitat impacts.

## 3.4: Recycling

Disposal of modules in landfills is not desired and (Sinha, et al., 2014) performed an aggressive experiment to establish the risk of exceeding toxicity levels in the event that Si or CdTe modules are deposited on an unsanitary landfill site. While within human health and ecological screening limits, their results indicated that all PV technologies need to be responsibly disposed of, as the concentrations of lead (which is toxic to human and plant life) from silicon PV in ground water, surface water, ambient air and soil are comparable to that of cadmium from CdTe. Recycling is the most sustainable manner in which modules can be handled at the end of their useful life, not only from an environmental impact perspective, but also in terms of resource efficiency. In addition, the recycling of CdTe PV offers an opportunity to decrease the primary energy demand of module manufacturing and would consequently reduce the associated energy payback period (Sinha, et al., 2012; Held, 2009).

The scale economy of growing waste streams and the decline of materials used within modules was identified by (Marwede & Reller, 2012) as two important, yet opposing aspects that will have a significant influence on the feasibility and economics of tellurium recovery in the future. Also mentioned is that the use of cadmium, as a toxic element, should require recycling despite the cost implications and that tellurium recovery should be regarded as an additional benefit. This benefit is enhanced by the fact that First Solar has demonstrated that a 99.999% refined product is achievable after recycling of the modules and that they are able to reuse this recycled product (Sinha, et al., 2012).

Environmentally sensitive metals, such as Pb, Cd, In, Ga, Se, Te, Cu and Ag, are common in the industry and therefore recycling is important for all PV technologies. In realising that the recycling of PV modules at the end of their useful 'life' will resolve any environmental concerns, as well as create an alternative Te (and Cd) resource, First Solar established the first global and comprehensive module recycling program in the PV industry in 2005. Recycling facilities are now operational in all First Solar manufacturing plants worldwide, with a total annual recycling capacity of approximately 26 000 tons (Experts, 2015). Besides the fact that recycling maximises resource recovery and increases the sustainability of PV, the socio-economic and environmental benefits of recycling are critical to minimise life cycle impacts. Inclusion of PV in the EU Waste Electrical & Electronic Equipment (WEEE) Directive is expected to yield approximately €16.5 billion in 2050 (Monier & Hestin, 2011), which would obviously create long-term economic benefits, including job creation.

First Solar's recycling process currently results in higher operating costs (compared to obtaining the semiconductor elements from the primary base metals mining industry by-product route), but the CdTe recycling process is continuously improving and the associated operational costs are decreasing. Coupled with this is the decreasing mass of semiconductor material usage per unit module (thinner PV layers), which could elevate recycled material to a primary resource level in the future. With currently over 177 GW, according to the latest Ren21 report (REN21, 2015), PV installed worldwide, recycling is crucial to managing large future PV waste volumes, and to reclaiming valuable and energy intensive materials. The First Solar modular recycle process (described below) is scalable, i.e. there would be no fundamental reason why high volumes of waste material could not be accommodated in localised recycling facilities in the future. The First Solar business objective would be to establish such 'regional / mobile' processing centres rather that to ship waste material around the globe (Experts, 2015).

## 3.5: Recycling process review

Recycling is the crucial 'cog' that closes the high-level loop between the manufacturing material inflow and the EOL waste material outflow, i.e. only if the recycling loop is functioning efficiently can PV become the true eco-efficient technology over the material life cycle.

After the visit to the recycling plant at the Perrysburg site and the related discussions, it was apparent that recyclability is fully integrated in the module design. The Change Management System (CMS) utilised by the actual high-tech manufacturing process is also used to track the recyclability of the manufacturing change and implement recycling process improvements.

The First Solar recycling process at the Perrysburg site has developed from a 10 t/day Version 1 (V1) batch process in 2006, to a 30 t/day Version 2 (V2) batch process in 2011. Besides the material handling improvements made to reduce erosive wear on the process equipment (by broken glass particles), in 2015 this process has now progressed to a third generation (V3) continuous process. Although still in a pilot phase, this process is more efficient and yields higher quality unrefined semiconductor material (USM) on a continuous basis.

The process consists of a number of unit operations that are relatively common to a typical metallurgical refinery: first, the EOL module scrap is reduced to a fraction of the original size in a shredder, after which the average particle size is reduced further by impact forces in a hammer mill. Although these comminution units operate dry, dust generation in the work environment is controlled by dust extraction / collection ducting to the appropriate dust collectors. The crushed particulates, consisting primarily of glass, laminate material and the semiconductor compounds are then withdrawn from a surge (holding) bin and oxidatively leached using sulphuric acid as the lixiviate and hydrogen peroxide as the oxidant. The semiconductor elements dissolve into the aqueous liquid phase, whilst the glass and laminate materials remain in the solid phase. The solid material is removed from the solution and progresses to a separation step where the encapsulation polymer lamination (film) layer and other plastic components are removed from the glass in a specific gravity float bath. The glass cullet exits through a spiral conveyer, is rinsed and then collected in a clean glass bin. The metals-bearing leaching solution progresses to a pH driven precipitation step where the Cd and Te elements are precipitated, followed by a filtration and washing step to produce the unrefined semiconductor material (USM) cake. This cake is packaged for further refining by a third party recycling partner who will again produce semiconductor grade CdTe for use in new modules. This refining process is discussed in detail in (Sinha, et al., 2012).

In terms of the current process recycling technology (described above), over 90% of the semiconductor and 90% of the glass material is recycled. About 90% of the module weight is recovered, most of it as glass, which will be reused in new glass products. The unrecovered material, i.e. the encapsulation polymer and small waste glass fraction, is handled in accordance with local waste disposal requirements, e.g. the plastics wastes could be disposed of at municipal incineration facilities whilst the inert glass waste could be safely disposed of at inert waste landfill sites. Any spillages (captured in the recycling plant bunted areas) or effluent is treated via the waste water effluent plant (discussed in the next section).

From an overall LCA perspective, the consumption of energy (electricity & transport fuel) and materials would increase the environmental impact of any PV recycling technology. Specifically to First Solar's CdTe recycling technology, recycling of one panel currently consumes around 4.4 kWh per $m^2$ panel (Sinha, et al., 2012).. Sulphuric acid (lixiviate), hydrogen peroxide (oxidant) and sodium hydroxide (neutralising agent) are the main chemical reagents consumed by the current CdTe recycling technology (Sinha, et al., 2012). On the other hand, environmental credits are gained in the form of the recycled CdTe, glass and Cu, which displace the primary sources of these products. The current recycling and waste water treatment routes limit Cd emissions to air and water to below $6\times10^{-9}$ and $9\times10^{-8}$ kg/$m^3$ respectively. Furthermore, to mitigate the risks associated with uncontrolled disposal, recycling is a convenient way to meet various regulatory and permit requirements (global regulatory developments will in future continue to limit PV disposal options; (Experts, 2015)).

Looking to the future, greater experience and rising disposal costs will likely result in recycling becoming economically attractive in the future. Smaller and mobile in-country recycling facilities will further reduce recycling costs by minimizing transport requirements and with operational costs expected to fall below hazardous waste disposal costs and high volume, fourth generation (V4) mobile recycling is expected to increase significantly (Experts, 2015). This, coupled with the above-mentioned socio-economic and environmental benefits, could drive the CdTe PV industry to become fully reliant on recycled end-of-life materials in the future, especially for metals like Te (Marwede & Reller, 2012).

First Solar's drive to collaborate with responsible PV EOL management in South Africa was discussed during the visit to the facility in Perrysburg (Experts, 2015) and First Solar stated that they offer recycling services in all regions of the world, including South Africa. The recycling costs will be optimised for the local market conditions but will also cover the logistic costs and the owner will always have the discretion to elect an alternate recycling vendor or responsible disposal method.

## 3.6: Water management (including waste water treatment)

Water consumption for the full life cycle of thermoelectric (e.g. coal and nuclear) power plants is substantial. This is especially relevant in water-scarce countries like South Africa, where dry cooling has become mandatory and has the potential to reduce the amount of water withdrawn for this purpose to some extent. In this regard, total life cycle water withdrawal per MWh is third lowest for PV (wind power and hydropower is lower; (Meldrum, et al., 2013)). Operational usage of water is related to (panel) cleaning, with relatively little consumption in the manufacturing process (approximately 1.5 litres/W produced in 2013; (First Solar, 2015)). Silicon-based PV has a higher life cycle water consumption level than CdTe due to the water needed for high-purity silicon production. The combined direct and indirect water usage for module production and preparation is 1 470 l/MWh for multi-Si compared to 575 l/MWh for CdTe. Includin power plant operation, these levels are 1 900 l/MWh for multi-Si and 800 l/MWh for CdTe. These values are at least an order of magnitude lower than that of conventional wet cooled fuel cycles such as coal (2 500 – 98 400 l/MWh) and gas fuel cycles (2 300 – 85 900 l/MWh). Of all electricity generation technologies, hydropower has the lowest withdrawal at 80 L/MWh, and that of biomass-to-electricity can be between 2 000 – 438 000 L/MWh depending on the biomass used and the conversion technology (Fthenakis & Kim, 2010).

The water usage of CdTe during the different components and life stages of the technology, i.e. module manufacturing, balance-of-system manufacturing, and maintenance as well as end-of-life activities have been determined by (Sinha, et al., 2013). The module accounted for the largest percentage of water withdrawal and activities related to end-of-life made up a very small portion of the total water withdrawal. The single largest contributor to total water consumption consists of the electricity used from the grid during module manufacturing. The production of steel used in the balance-of-system contributes second most to the total. Although comparable to the results of (Fthenakis & Kim, 2010), results obtained here are lower and estimated at a total life cycle withdrawal of 382 – 425 l/MWh. Another positive aspect of the low water withdrawal of CdTe is attained by calculating how much life cycle water withdrawal can be displaced from conventional grid electricity. This was estimated to be between 1 700 – 5 600 l/MWh (Sinha, et al., 2013). It is, of course, important to note that the location of a power plant would also influence the amount of water used due to the variation in different environmental factors such as dust and soil cover. In the same manner as technology improvements take place in order to minimise the amount of tellurium needed, it would also be valuable to the sustainability of CdTe modules in order to adapt manufacturing processes, operations and maintenance procedures to decrease the amount of water used during the technologies life cycle.

In terms of waste treatment, only the water used in the manufacturing process contains trace amounts of Cd (up to 30 mg/L Cd) prior to treatment. For this reason, no waste water leaves any of the First Solar manufacturing sites until it is treated, tested and verified as safe to discharge. The First Solar waste water process flow diagram begins at the metals water collection tank. The primary metals removal step relies on conventional metal hydrolysis by adding caustic soda, NaOH (neutralising agent), to raise the pH from about 5 to a value of 12. The resulting sodium chloride (NaCl) solution holds no environmental restrictions.

The precipitation of the solid particulates is conducted in the presence of iron(III) chloride (coagulant) and flocculent to improve the settling and filterability of the solids phase. After clarification, the underflow progresses to a filter press where the solid filter cake (containing the metals) is removed for recycling (discharged every 12 hrs). The primary filtrate is recycled to the waste water collection tank. If required, the clarifier overflow is pumped to a polishing filter (which can remove any ultra-fine particles down to 0 – 6 mg/l). First Solar also implemented ion exchange (IX) polishing technology to further reduce Cd levels to less than 0.020 mg/L (typically 0.010 mg/L). The standard metals precipitation technology (without polishing) will remove Cd to approximately 0.1 mg/L, as required by most municipalities. At First Solar's manufacturing plant in Malaysia, the waste water enters at 15 – 80 mg/l Cd and is discharged at levels as low as 0.005 mg/l Cd (Experts, 2015).

In terms of the SHE aspects related to water management, dedicated / monitored chemical storage facilities are employed, storm-water outflow is managed and no chemicals are used outside covered buildings. Bunted secondary containment of containers / vessels is also a standard feature in all the manufacturing and recycling areas. All factories are equipped with state-of-the-art analytical capabilities for 24/7 in-house water testing of Cd, Cu and other parameters such as pH (weekly composite samples are also sent to outside laboratories for analysis). Finally, all waste water systems operate in a batch discharge mode, i.e. after treatment, water is collected in holding tanks and these tanks are sampled and tested to confirm compliance with permitting limits before discharging. If not compliant, the water is sent back for re-treatment internally.

# Conclusion

The First Solar thin film CdTe technology is suited for South Africa, with warmer climate areas generating a higher yield with the CdTe modules than for single or multi-crystalline silicon PV modules. Advances in the double glass CdTe module capability is allowing for the use of higher system voltages, thereby increasing the energy density and reducing the size and cost of power inverters.

The active component, CdTe, of the First Solar modules is a solid and stable compound that is insoluble in water and has a high melting point. These factors limit the potential exposure to humans and in the event of potential exposure during extreme events, CdTe is at least 8.9 times safer than Cd with respect to acute exposure via inhalation or ingestion. When considering other sources of cadmium exposure, manufacturing PV modules from CdTe should be regarded as a responsible and safe way to beneficially utilise a by-product of industrial processes. It is important to understand that during normal operation CdTe modules emit no pollutants to the air, water or soil.

CdTe PV modules also have shorter energy payback times and lower life cycle $CO_2$ emissions than any other PV modules and have comparable or less $CO_2$ emissions than nuclear and wind technologies. The impact that large-scale PV plants have on land use is better than that for coal power plants over the fuel cycle and improves with the lifetime of the plant. The specific location of a PV plant will determine the actual impact, where desert like locations will show the least amount of impact. To reduce the impact on the environment, First Solar advocates the recycling of solar PV modules.

As part of the First Solar recycling and manufacturing process, the waste water is treated to an acceptable level within their permit specifications and tested before it is released from site. The water consumption during manufacturing and operation compares favourably against other electricity generation technologies, in part because solar PV plants utilise passive cooling and this is very important in a water scarce country like South Africa.

First Solar's CdTe thin film technology modules are a technically feasible, environmentally friendly and safe option to producing electricity in South Africa.

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# Health and Safety Impacts of Solar Photovoltaics

The increasing presence of utility-scale solar photovoltaic (PV) systems (sometimes referred to as solar farms) is a rather new development in North Carolina's landscape. Due to the new and unknown nature of this technology, it is natural for communities near such developments to be concerned about health and safety impacts. Unfortunately, the quick emergence of utility-scale solar has cultivated fertile grounds for myths and half-truths about the health impacts of this technology, which can lead to unnecessary fear and conflict.

Photovoltaic (PV) technologies and solar inverters are not known to pose any significant health dangers to their neighbors. The most important dangers posed are increased highway traffic during the relative short construction period and dangers posed to trespassers of contact with high voltage equipment. This latter risk is mitigated by signage and the security measures that industry uses to deter trespassing. As will be discussed in more detail below, risks of site contamination are much less than for most other industrial uses because PV technologies employ few toxic chemicals and those used are used in very small quantities. Due to the reduction in the pollution from fossil-fuel-fired electric generators, the overall impact of solar development on human health is overwhelmingly positive. This pollution reduction results from a partial replacement of fossil-fuel fired generation by emission-free PV-generated electricity, which reduces harmful sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), and fine particulate matter ($PM_{2.5}$). Analysis from the National Renewable Energy Laboratory and the Lawrence Berkeley National Laboratory, both affiliates of the U.S. Department of Energy, estimates the health-related air quality benefits to the southeast region from solar PV generators to be worth 8.0 ¢ per kilowatt-hour of solar generation.[1] This is in addition to the value of the electricity and suggests that the air quality benefits of solar are worth more than the electricity itself.

Even though we have only recently seen large-scale installation of PV technologies, the technology and its potential impacts have been studied since the 1950s. A combination of this solar-specific research and general scientific research has led to the scientific community having a good understanding of the science behind potential health and safety impacts of solar energy. This paper utilizes the latest scientific literature and knowledge of solar practices in N.C. to address the health and safety risks associated with solar PV technology. These risks are extremely small, far less than those associated with common activities such as driving a car, and vastly outweighed by health benefits of the generation of clean electricity.

This paper addresses the potential health and safety impacts of solar PV development in North Carolina, organized into the following four categories:

(1) Hazardous Materials
(2) Electromagnetic Fields (EMF)
(3) Electric Shock and Arc Flash
(4) Fire Safety

# 1. Hazardous Materials

One of the more common concerns towards solar is that the panels (referred to as “modules” in the solar industry) consist of toxic materials that endanger public health. However, as shown in this section, solar energy systems may contain small amounts of toxic materials, but these materials do not endanger public health. To understand potential toxic hazards coming from a solar project, one must understand system installation, materials used, the panel end-of-life protocols, and system operation. This section will examine these aspects of a solar farm and the potential for toxicity impacts in the following subsections:

(1.2) Project Installation/Construction
(1.2) System Components
    1.2.1 Solar Panels: Construction and Durability
    1.2.2 Photovoltaic technologies
        (a) Crystalline Silicon
        (b) Cadmium Telluride (CdTe)
        (c) CIS/CIGS
    1.2.3 Panel End of Life Management
    1.2.4 Non-panel System Components
(1.3) Operations and Maintenance

## 1.1 Project Installation/Construction

The system installation, or construction, process does not require toxic chemicals or processes. The site is mechanically cleared of large vegetation, fences are constructed, and the land is surveyed to layout exact installation locations. Trenches for underground wiring are dug and support posts are driven into the ground. The solar panels are bolted to steel and aluminum support structures and wired together. Inverter pads are installed, and an inverter and transformer are installed on each pad. Once everything is connected, the system is tested, and only then turned on.

*Figure 1: Utility-scale solar facility (5 $MW_{AC}$) located in Catawba County. Source: Strata Solar*

## 1.2 System Components

### 1.2.1 Solar Panels: Construction and Durability

Solar PV panels typically consist of glass, polymer, aluminum, copper, and semiconductor materials that can be recovered and recycled at the end of their useful life.[2] Today there are two PV technologies used in PV panels at utility-scale solar facilities, silicon, and thin film. As of 2016, all thin film used in North Carolina solar facilities are cadmium telluride (CdTe) panels from the US manufacturer First Solar, but there are other thin film PV panels available on the market, such as Solar Frontier's CIGS panels. Crystalline silicon technology consists of silicon wafers which are made into cells and assembled into panels, thin film technologies consist of thin layers of semiconductor material deposited onto glass, polymer or metal substrates. While there are differences in the components and manufacturing processes of these two types of solar technologies, many aspects of their PV panel construction are very similar. Specifics about each type of PV chemistry as it relates to toxicity are covered in subsections a, b, and c in section 1.2.2; on crystalline silicon, cadmium telluride, and CIS/CIGS respectively. The rest of this section applies equally to both silicon and thin film panels.

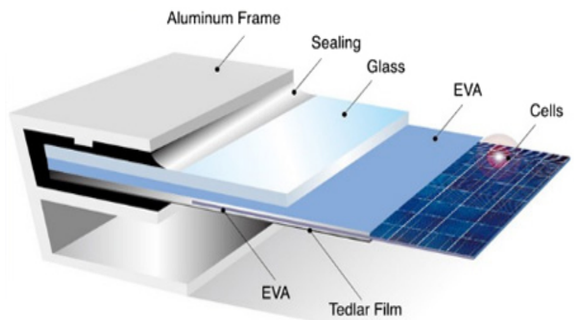


*Figure 2: Components of crystalline silicon panels. The vast majority of silicon panels consist of a glass sheet on the topside with an aluminum frame providing structural support. Image Source: www.riteksolar.com.tw*

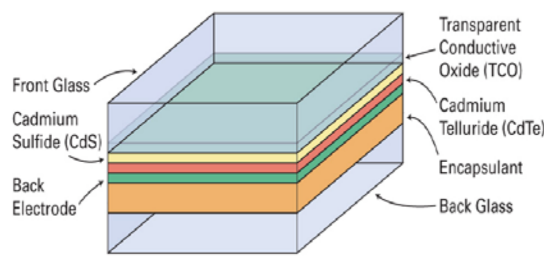


*Figure 3: Layers of a common frameless thin-film panel (CdTe). Many thin film panels are frameless, including the most common thin-film panels, First Solar's CdTe. Frameless panels have protective glass on both the front and back of the panel. Layer thicknesses not to scale. Image Source: www.homepower.com*

To provide decades of corrosion-free operation, PV cells in PV panels are encapsulated from air and moisture between two layers of plastic. The encapsulation layers are protected on the top with a layer of tempered glass and on the backside with a polymer sheet. Frameless modules include a protective layer of glass on the rear of the panel, which may also be tempered. The plastic ethylene-vinyl acetate (EVA) commonly provides the cell encapsulation. For decades, this same material has been used between layers of tempered glass to give car windshields and hurricane windows their great strength. In the same way that a car windshield cracks but stays intact, the EVA layers in PV panels keep broken panels intact (see Figure 4). Thus, a damaged module does not generally create small pieces of debris; instead, it largely remains together as one piece.


*Figure 4: The mangled PV panels in this picture illustrate the nature of broken solar panels; the glass cracks but the panel is still in one piece. Image Source: http://img.alibaba.com/photo/115259576/broken_solar_panel.jpg*

PV panels constructed with the same basic components as modern panels have been installed across the globe for well over thirty years.[3] The long-term durability and performance demonstrated over these decades, as well as the results of accelerated lifetime testing, helped lead to an industry-standard 25-year power production warranty for PV panels. These power warranties warrant a PV panel to produce at least 80% of their original nameplate production after 25 years of use. A recent SolarCity and DNV GL study reported that today's quality PV panels should be expected to reliably and efficiently produce power for thirty-five years.[4]

Local building codes require all structures, including ground mounted solar arrays, to be engineered to withstand anticipated wind speeds, as defined by the local wind speed requirements. Many racking products are available in versions engineered for wind speeds of up to 150 miles per hour, which is significantly higher than the wind speed requirement anywhere in North Carolina. The strength of PV mounting structures were demonstrated during Hurricane Sandy in 2012 and again during Hurricane Matthew in 2016. During Hurricane Sandy, the many large-scale solar facilities in New Jersey and New York at that time suffered only minor damage.[5] In the fall of 2016, the US and Caribbean experienced destructive winds and torrential rains from Hurricane Matthew, yet one leading solar tracker manufacturer reported that their numerous systems in the impacted area received zero damage from wind or flooding.[6]

In the event of a catastrophic event capable of damaging solar equipment, such as a tornado, the system will almost certainly have property insurance that will cover the cost to cleanup and repair the project. It is in the best interest of the system owner to protect their investment against such risks. It is also in their interest to get the project repaired and producing full power as soon as possible. Therefore, the investment in adequate insurance is a wise business practice for the system owner. For the same reasons, adequate insurance coverage is also generally a requirement of the bank or firm providing financing for the project.

### 1.2.2 Photovoltaic (PV) Technologies

a. **Crystalline Silicon**

This subsection explores the toxicity of silicon-based PV panels and concludes that they do not pose a material risk of toxicity to public health and safety. Modern crystalline silicon PV panels, which account for over 90% of solar PV panels installed today, are, more or less, a commodity product. The overwhelming majority of panels installed in North Carolina are crystalline silicon panels that are informally classified as Tier I panels. Tier I panels are from well-respected manufacturers that have a good chance of being able to honor warranty claims. Tier I panels are understood to be of high quality, with predictable performance, durability, and content. Well over 80% (by weight) of the content of a PV panel is the tempered glass front and the aluminum frame, both of which are common building materials. Most of the remaining portion are common plastics, including polyethylene terephthalate in the backsheet, EVA encapsulation of the PV cells, polyphenyl ether in the junction box, and polyethylene insulation on the wire leads. The active, working components of the system are the silicon photovoltaic cells, the small electrical leads connecting them together, and to the wires coming out of the back of the panel. The electricity generating and conducting components makeup less than 5% of the weight of most panels. The PV cell itself is nearly 100% silicon, and silicon is the second most common element in the Earth's crust. The silicon for PV cells is obtained by high-temperature processing of quartz sand ($SiO_2$) that removes its oxygen molecules. The refined silicon is converted to a PV cell by adding extremely small amounts of boron and phosphorus, both of which are common and of very low toxicity.

The other minor components of the PV cell are also generally benign; however, some contain lead, which is a human toxicant that is particularly harmful to young children. The minor components include an extremely thin antireflective coating (silicon nitride or titanium dioxide), a thin layer of aluminum on the rear, and thin strips of silver alloy that are screen-printed on the front and rear of cell.[7] In order for the front and rear electrodes to make effective electrical contact with the proper layer of the PV cell, other materials (called glass frit) are mixed with the silver alloy and then heated to etch the metals into the cell. This glass frit historically contains a small amount of lead (Pb) in the form of lead oxide. The 60 or 72 PV cells in a PV panel are connected by soldering thin solder-covered copper tabs from the back of one cell to the front of the next cell. Traditionally a tin-based solder containing some lead (Pb) is used, but some manufacturers have switched to lead-free solder. The glass frit and/or the solder may contain trace amounts of other metals, potentially including some with human toxicity such as cadmium. However, testing to simulate the potential for leaching from broken panels, which is discussed in more detail below, did not find a potential toxicity threat from these trace elements. Therefore, the tiny amount of lead in the grass frit and the solder is the only part of silicon PV panels with a potential to create a negative health impact. However, as described below, the very limited amount of lead involved and its strong physical and chemical attachment to other components of the PV panel means that even in worst-case scenarios the health hazard it poses is insignificant.

As with many electronic industries, the solder in silicon PV panels has historically been a lead-based solder, often 36% lead, due to the superior properties of such solder. However, recent advances in lead-free solders have spurred a trend among PV panel manufacturers to reduce or remove the lead in their panels. According to the 2015 Solar Scorecard from the Silicon Valley Toxics Coalition, a group that tracks environmental responsibility of photovoltaic panel manufacturers, fourteen companies (increased from twelve companies in 2014) manufacture PV panels certified to meet the European Restriction of

Hazardous Substances (RoHS) standard. This means that the amount of cadmium and lead in the panels they manufacture fall below the RoHS thresholds, which are set by the European Union and serve as the world's de facto standard for hazardous substances in manufactured goods.[8] The Restriction of Hazardous Substances (RoHS) standard requires that the maximum concentration found in any homogenous material in a produce is less than 0.01% cadmium and less than 0.10% lead, therefore, any solder can be no more than 0.10% lead.[9]

While some manufacturers are producing PV panels that meet the RoHS standard, there is no requirement that they do so because the RoHS Directive explicitly states that the directive does not apply to photovoltaic panels.[10] The justification for this is provided in item 17 of the current RoHS Directive: "The development of renewable forms of energy is one of the Union's key objectives, and the contribution made by renewable energy sources to environmental and climate objectives is crucial. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources (4) recalls that there should be coherence between those objectives and other Union environmental legislation. Consequently, this Directive should not prevent the development of renewable energy technologies that have no negative impact on health and the environment and that are sustainable and economically viable."

The use of lead is common in our modern economy. However, only about 0.5% of the annual lead consumption in the U.S. is for electronic solder for all uses; PV solder makes up only a tiny portion of this 0.5%. Close to 90% of lead consumption in the US is in batteries, which do not encapsulate the pounds of lead contained in each typical automotive battery. This puts the lead in batteries at great risk of leaching into the environment. Estimates for the lead in a single PV panel with lead-based solder range from 1.6 to 24 grams of lead, with 13g (less than half of an ounce) per panel seen most often in the literature.[11] At 13 g/panel[12], each panel contains one-half of the lead in a typical 12-gauge shotgun shell. This amount equates to roughly 1/750$^{th}$ of the lead in a single car battery. In a panel, it is all durably encapsulated from air or water for the full life of the panel.[14]

As indicated by their 20 to 30-year power warranty, PV modules are designed for a long service life, generally over 25 years. For a panel to comply with its 25-year power warranty, its internal components, including lead, must be sealed from any moisture. Otherwise, they would corrode and the panel's output would fall below power warranty levels. Thus, the lead in operating PV modules is not at risk of release to the environment during their service lifetime. In extreme experiments, researchers have shown that lead can leach from crushed or pulverized panels.[15, 16] However, more real-world tests designed to represent typical trash compaction that are used to classify waste as hazardous or non-hazardous show no danger from leaching.[17, 18] For more information about PV panel end-of-life, see the Panel Disposal section.

As illustrated throughout this section, silicon-based PV panels do not pose a material threat to public health and safety. The only aspect of the panels with potential toxicity concerns is the very small amount of lead in some panels. However, any lead in a panel is well sealed from environmental exposure for the operating lifetime of the solar panel and thus not at risk of release into the environment.

### b. Cadmium Telluride (CdTe) PV Panels

This subsection examines the components of a cadmium telluride (CdTe) PV panel. Research demonstrates that they pose negligible toxicity risk to public health and safety while significantly reducing the public's exposure to cadmium by reducing coal emissions. As of mid-2016, a few hundred MWs of cadmium telluride (CdTe) panels, all manufactured by the U.S. company First Solar, have been installed in North Carolina.

Questions about the potential health and environmental impacts from the use of this PV technology are related to the concern that these panels contain cadmium, a toxic heavy metal. However, scientific studies have shown that cadmium telluride differs from cadmium due to its high chemical and thermal stability.[19] Research has shown that the tiny amount of cadmium in these panels does not pose a health or safety risk.[20] Further, there are very compelling reasons to welcome its adoption due to reductions in unhealthy pollution associated with burning coal. Every GWh of electricity generated by burning coal produces about 4 grams of cadmium air emissions.[21] Even though North Carolina produces a significant fraction of our electricity from coal, electricity from solar offsets much more natural gas than coal due to natural gas plants being able to adjust their rate of production more easily and quickly. If solar electricity offsets 90% natural gas and 10% coal, each 5-megawatt (5 $MW_{AC}$, which is generally 7 $MW_{DC}$) CdTe solar facility in North Carolina keeps about 157 grams, or about a third of a pound, of cadmium *out of* our environment.[22, 23]

Cadmium is toxic, but all the approximately 7 grams of cadmium in one CdTe panel is in the form of a chemical compound cadmium telluride, [24] which has 1/100th the toxicity of free cadmium.[25] Cadmium telluride is a very stable compound that is non-volatile and non-soluble in water. Even in the case of a fire, research shows that less than 0.1% of the cadmium is released when a CdTe panel is exposed to fire. The fire melts the glass and encapsulates over 99.9% of the cadmium in the molten glass.[27]

It is important to understand the source of the cadmium used to manufacture CdTe PV panels. The cadmium is a byproduct of zinc and lead refining. The element is collected from emissions and waste streams during the production of these metals and combined with tellurium to create the CdTe used in PV panels. If the cadmium were not collected for use in the PV panels or other products, it would otherwise either be stockpiled for future use, cemented and buried, or disposed of.[28] Nearly all the cadmium in old or broken panels can be recycled which can eventually serve as the primary source of cadmium for new PV panels.[29]

Similar to silicon-based PV panels, CdTe panels are constructed of a tempered glass front, one instead of two clear plastic encapsulation layers, and a rear heat strengthened glass backing (together >98% by weight). The final product is built to withstand exposure to the elements without significant damage for over 25 years. While not representative of damage that may occur in the field or even at a landfill, laboratory evidence has illustrated that when panels are ground into a fine powder, very acidic water is able to leach portions of the cadmium and tellurium,[30] similar to the process used to recycle CdTe panels. Like many silicon-based panels, CdTe panels are reported (as far back ask 1998[31]) to pass the EPA's Toxic Characteristic Leaching Procedure (TCLP) test, which tests the potential for crushed panels in a landfill to leach hazardous substances into groundwater.[32] Passing this test means that they are classified as non-hazardous waste and can be deposited in landfills.[33, 34] For more information about PV panel end-of-life, see the Panel Disposal section.

There is also concern of environmental impact resulting from potential catastrophic events involving CdTe PV panels. An analysis of worst-case scenarios for environmental impact from CdTe PV panels, including earthquakes, fires, and floods, was conducted by the University of Tokyo in 2013. After reviewing the extensive international body of research on CdTe PV technology, their report concluded, "Even in the worst-case scenarios, it is unlikely that the Cd concentrations in air and sea water will exceed the environmental regulation values."[35] In a worst-case scenario of damaged panels abandoned on the ground, insignificant amounts of cadmium will leach from the panels. This is because this scenario is much less conducive (larger module pieces, less acidity) to leaching than the conditions of the EPA's TCLP test used to simulate landfill conditions, which CdTe panels pass.[36]

First Solar, a U.S. company, and the only significant supplier of CdTe panels, has a robust panel take-back and recycling program that has been operating commercially since 2005.[37] The company states that it is "committed to providing a commercially attractive recycling solution for photovoltaic (PV) power plant and module owners to help them meet their module (end of life) EOL obligation simply, cost-effectively and responsibly." First Solar global recycling services to their customers to collect and recycle panels once they reach the end of productive life whether due to age or damage. These recycling service agreements are structured to be financially attractive to both First Solar and the solar panel owner. For First Solar, the contract provides the company with an affordable source of raw materials needed for new panels and presumably a diminished risk of undesired release of Cd. The contract also benefits the solar panel owner by allowing them to avoid tipping fees at a waste disposal site. The legal contract helps provide peace of mind by ensuring compliance by both parties when considering the continuing trend of rising disposal costs and increasing regulatory requirements.

c. **CIS/CIGS and other PV technologies**

Copper indium gallium selenide PV technology, often referred to as CIGS, is the second most common type of thin-film PV panel but a distant second behind CdTe. CIGS cells are composed of a thin layer of copper, indium, gallium, and selenium on a glass or plastic backing. None of these elements are very toxic, although selenium is a regulated metal under the Federal Resource Conservation and Recovery Act (RCRA).[38] The cells often also have an extremely thin layer of cadmium sulfide that contains a tiny amount of cadmium, which is toxic. The promise of high efficiency CIGS panels drove heavy investment in this technology in the past. However, researchers have struggled to transfer high efficiency success in the lab to low-cost full-scale panels in the field.[39] Recently, a CIGS manufacturer based in Japan, Solar Frontier, has achieved some market success with a rigid, glass-faced CIGS module that competes with silicon panels. Solar Frontier produces the majority of CIS panels on the market today.[40] Notably, these panels are RoHS compliant,[41] thus meeting the rigorous toxicity standard adopted by the European Union even thought this directive exempts PV panels. The authors are unaware of any completed or proposed utility-scale system in North Carolina using CIS/CIGS panels.

### 1.2.3 Panel End-of-Life Management

Concerns about the volume, disposal, toxicity, and recycling of PV panels are addressed in this subsection. To put the volume of PV waste into perspective, consider that by 2050, when PV systems installed in 2020 will reach the end of their lives, it is estimated that the global annual PV panel waste tonnage will be 10% of the 2014 global e-waste tonnage.[42] In the U.S., end-of-life disposal of solar products is governed by the Federal Resource Conservation and Recovery Act (RCRA), as well as state policies in some situations. RCRA separates waste into hazardous (not accepted at ordinary landfill) and solid waste (generally accepted at ordinary landfill) based on a series of rules. According to RCRA, the way to determine if a PV panel is classified as hazardous waste is the Toxic Characteristic Leaching Procedure (TCLP) test. This EPA test is designed to simulate landfill disposal and determine the risk of hazardous substances leaching out of the landfill.[43,44,45] Multiple sources report that most modern PV panels (both crystalline silicon and cadmium telluride) pass the TCLP test.[46,47] Some studies found that some older (1990s) crystalline silicon panels, and perhaps some newer crystalline silicon panels (specifics are not given about vintage of panels tested), do not pass the lead (Pb) leachate limits in the TCLP test.[48,49]

The test begins with the crushing of a panel into centimeter-sized pieces. The pieces are then mixed in an acid bath. After tumbling for eighteen hours, the fluid is tested for forty hazardous substances that all must be below specific threshold levels to pass the test. Research comparing TCLP conditions to conditions of damaged panels in the field found that simulated landfill conditions provide overly conservative estimates of leaching for field-damaged panels.[50] Additionally, research in Japan has found no detectable Cd leaching from cracked CdTe panels when exposed to simulated acid rain.[51]

Although modern panels can generally be landfilled, they can also be recycled. Even though recent waste volume has not been adequate to support significant PV-specific recycling infrastructure, the existing recycling industry in North Carolina reports that it recycles much of the current small volume of broken PV panels. In an informal survey conducted by the NC Clean Energy Technology Center survey in early 2016, seven of the eight large active North Carolina utility-scale solar developers surveyed reported that they send damaged panels back to the manufacturer and/or to a local recycler. Only one developer reported sending damaged panels to the landfill.

The developers reported at that time that they are usually paid a small amount per panel by local recycling firms. In early 2017, a PV developer reported that a local recycler was charging a small fee per panel to recycle damaged PV panels. The local recycling firm known to authors to accept PV panels described their current PV panel recycling practice as of early 2016 as removing the aluminum frame for local recycling and removing the wire leads for local copper recycling. The remainder of the panel is sent to a facility for processing the non-metallic portions of crushed vehicles, referred to as "fluff" in the recycling industry.[52] This processing within existing general recycling plants allows for significant material recovery of major components, including glass which is 80% of the module weight, but at lower yields than PV-specific recycling plants. Notably almost half of the material value in a PV panel is in the few grams of silver contained in almost every PV panel produced today. In the long-term, dedicated PV panel recycling plants can increase treatment capacities and maximize revenues resulting in better output quality and the ability to recover a greater fraction of the useful materials.[53] PV-specific panel recycling technologies have been researched and implemented to some extent for the past decade, and have been shown to be able to recover over 95% of PV material (semiconductor) and over 90% of the glass in a PV panel.[54]

A look at global PV recycling trends hints at the future possibilities of the practice in our country. Europe installed MW-scale volumes of PV years before the U.S. In 2007, a public-private partnership between the European Union and the solar industry set up a voluntary collection and recycling system called PV CYCLE. This arrangement was later made mandatory under the EU's WEEE directive, a program for waste electrical and electronic equipment.[55] Its member companies (PV panel producers) fully finance the association. This makes it possible for end-users to return the member companies' defective panels for recycling at any of the over 300 collection points around Europe without added costs. Additionally, PV CYCLE will pick up batches of 40 or more used panels at no cost to the user. This arrangement has been very successful, collecting and recycling over 13,000 tons by the end of 2015.[56]

In 2012, the WEEE Directive added the end-of-life collection and recycling of PV panels to its scope.[57] This directive is based on the principle of extended-producer-responsibility. It has a global impact because producers that want to sell into the EU market are legally responsible for end-of-life management. Starting in 2018, this directive targets that 85% of PV products "put in the market" in Europe are recovered and 80% is prepared for reuse and recycling.

The success of the PV panel collection and recycling practices in Europe provides promise for the future of recycling in the U.S. In mid-2016, the US Solar Energy Industry Association (SEIA) announced that they are starting a national solar panel recycling program with the guidance and support of many leading PV panel producers.[58] The program will aggregate the services offered by recycling vendors and PV manufacturers, which will make it easier for consumers to select a cost-effective and environmentally responsible end-of-life management solution for their PV products. According to SEIA, they are planning the program in an effort to make the entire industry landfill-free. In addition to the national recycling network program, the program will provide a portal for system owners and consumers with information on how to responsibly recycle their PV systems.

While a cautious approach toward the potential for negative environmental and/or health impacts from retired PV panels is fully warranted, this section has shown that the positive health impacts of reduced emissions from fossil fuel combustion from PV systems more than outweighs any potential risk. Testing shows that silicon and CdTe panels are both safe to dispose of in landfills, and are also safe in worst case conditions of abandonment or damage in a disaster. Additionally, analysis by local engineers has found that the current salvage value of the equipment in a utility scale PV facility generally exceeds general contractor estimates for the cost to remove the entire PV system.[59, 60, 61]

### 1.2.4 Non-Panel System Components (racking, wiring, inverter, transformer)

While previous toxicity subsections discussed PV panels, this subsection describes the non-panel components of utility-scale PV systems and investigates any potential public health and safety concerns. The most significant non-panel component of a ground-mounted PV system is the mounting structure of the rows of panels, commonly referred to as "racking". The vertical post portion of the racking is galvanized steel and the remaining above-ground racking components are either galvanized steel or aluminum, which are both extremely common and benign building materials. The inverters that make the solar generated electricity ready to send to the grid have weather-proof steel enclosures that protect the working components from the elements. The only fluids that they might contain are associated with their cooling systems, which are not unlike the cooling system in a computer. Many inverters today are RoHS compliant.

The electrical transformers (to boost the inverter output voltage to the voltage of the utility connection point) do contain a liquid cooling oil. However, the fluid used for that function is either a non-toxic mineral oil or a biodegradable non-toxic vegetable oil, such as BIOTEMP from ABB. These vegetable transformer oils have the additional advantage of being much less flammable than traditional mineral oils. Significant health hazards are associated with old transformers containing cooling oil with toxic PCBs. Transfers with PCB-containing oil were common before PCBs were outlawed in the U.S. in 1979. PCBs still exist in older transformers in the field across the country.

Other than a few utility research sites, there are no batteries on- or off-site associated with utility-scale solar energy facilities in North Carolina, avoiding any potential health or safety concerns related to battery technologies. However, as battery technologies continue to improve and prices continue to decline we are likely to start seeing some batteries at solar facilities. Lithium ion batteries currently dominate the world utility-scale battery market, which are not very toxic. No non-panel system components were found to pose any health or environmental dangers.

## 1.4 Operations and Maintenance – Panel Washing and Vegetation Control

Throughout the eastern U.S., the climate provides frequent and heavy enough rain to keep panels adequately clean. This dependable weather pattern eliminates the need to wash the panels on a regular basis. Some system owners may choose to wash panels as often as once a year to increase production, but most in N.C. do not regularly wash any PV panels. Dirt build up over time may justify panel washing a few times over the panels' lifetime; however, nothing more than soap and water are required for this activity.

The maintenance of ground-mounted PV facilities requires that vegetation be kept low, both for aesthetics and to avoid shading of the PV panels. Several approaches are used to maintain vegetation at NC solar facilities, including planting of limited-height species, mowing, weed-eating, herbicides, and grazing livestock (sheep). The following descriptions of vegetation maintenance practices are based on interviews with several solar developers as well as with three maintenance firms that together are contracted to maintain well over 100 of the solar facilities in N.C. The majority of solar facilities in North Carolina maintain vegetation primarily by mowing. Each row of panels has a single row of supports, allowing sickle mowers to mow under the panels. The sites usually require mowing about once a month during the growing season. Some sites employ sheep to graze the site, which greatly reduces the human effort required to maintain the vegetation and produces high quality lamb meat.[62]

In addition to mowing and weed eating, solar facilities often use some herbicides. Solar facilities generally do not spray herbicides over the entire acreage; rather they apply them only in strategic locations such as at the base of the perimeter fence, around exterior vegetative buffer, on interior dirt roads, and near the panel support posts. Also unlike many row crop operations, solar facilities generally use only general use herbicides, which are available over the counter, as opposed to restricted use herbicides commonly used in commercial agriculture that require a special restricted use license. The herbicides used at solar facilities are primarily 2-4-D and glyphosate (Round-up®), which are two of the most common herbicides used in lawns, parks, and agriculture across the country. One maintenance firm that was interviewed sprays the grass with a class of herbicide known as a growth regulator in order to slow the growth of grass so that mowing is only required twice a year. Growth regulators are commonly used on highway roadsides and golf courses for the same purpose. A commercial pesticide applicator license is required for anyone other than the landowner to apply herbicides, which helps ensure that all applicators are adequately educated about proper herbicide use and application. The license must be renewed annually and requires passing of a certification exam appropriate to the area in which the applicator wishes to work. Based on the limited data available, it appears that solar facilities in N.C. generally use significantly less herbicides per acre than most commercial agriculture or lawn maintenance services.

## 2. Electromagnetic Fields (EMF)

PV systems do not emit any material during their operation; however, they do generate electromagnetic fields (EMF), sometimes referred to as radiation. EMF produced by electricity is non-ionizing radiation, meaning the radiation has enough energy to move atoms in a molecule around (experienced as heat), but not enough energy to remove electrons from an atom or molecule (ionize) or to damage DNA. As shown below, modern humans are all exposed to EMF throughout our daily lives without negative health impact. Someone outside of the fenced perimeter of a solar facility is not exposed to significant EMF from the solar facility. Therefore, there is no negative health impact from the EMF produced in a solar farm. The following paragraphs provide some additional background and detail to support this conclusion.

Since the 1970s, some have expressed concern over potential health consequences of EMF from electricity, but no studies have ever shown this EMF to cause health problems.[63] These concerns are based on some epidemiological studies that found a slight increase in childhood leukemia associated with average exposure to residential power-frequency magnetic fields above 0.3 to 0.4 µT (microteslas) (equal to 3.0 to 4.0 mG (milligauss)). µT and mG are both units used to measure magnetic field strength. For comparison, the average exposure for people in the U.S. is one mG or 0.1 µT, with about 1% of the population with an average exposure in excess of 0.4 µT (or 4 mG).[64] These epidemiological studies, which found an association but not a causal relationship, led the World Health Organization's International Agency for Research on Cancer (IARC) to classify ELF magnetic fields as "possibly carcinogenic to humans". Coffee also has this classification. This classification means there is limited evidence but not enough evidence to designate as either a "probable carcinogen" or "human carcinogen". Overall, there is very little concern that ELF EMF damages public health. The only concern that does exist is for long-term exposure above 0.4 µT (4 mG) that may have some connection to increased cases of childhood leukemia. In 1997, the National Academies of Science were directed by Congress to examine this concern and concluded:

> "Based on a comprehensive evaluation of published studies relating to the effects of power-frequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects, or reproductive and developmental effects."[65]

There are two aspects to electromagnetic fields, an electric field and a magnetic field. The electric field is generated by voltage and the magnetic field is generated by electric current, i.e., moving electrons. A task group of scientific experts convened by the World Health Organization (WHO) in 2005 concluded that there were no substantive health issues related to *electric* fields (0 to 100,000 Hz) at levels generally encountered by members of the public.[66] The relatively low voltages in a solar facility and the fact that electric fields are easily shielded (i.e., blocked) by common materials, such as plastic, metal, or soil means that there is no concern of negative health impacts from the electric fields generated by a solar facility. Thus, the remainder of this section addresses magnetic fields. Magnetic fields are not shielded by most common materials and thus can easily pass through them. Both types of fields are strongest close to the source of electric generation and weaken quickly with distance from the source.

The direct current (DC) electricity produced by PV panels produce stationary (0 Hz) electric and magnetic fields. Because of minimal concern about potential risks of stationary fields, little scientific research has examined stationary fields' impact on human health.[67] In even the largest PV facilities, the DC voltages and currents are not very high. One can illustrate the weakness of the EMF generated by a PV panel by placing a compass on an operating solar panel and observing that the needle still points north.

While the electricity throughout the majority of a solar site is DC electricity, the inverters convert this DC electricity to alternating current (AC) electricity matching the 60 Hz frequency of the grid. Therefore, the inverters and the wires delivering this power to the grid are producing non-stationary EMF, known as extremely low frequency (ELF) EMF, normally oscillating with a frequency of 60 Hz. This frequency is at the low-energy end of the electromagnetic spectrum. Therefore, it has less energy than other commonly encountered types of non-ionizing radiation like radio waves, infrared radiation, and visible light.

The wide use of electricity results in background levels of ELF EMFs in nearly all locations where people spend time – homes, workplaces, schools, cars, the supermarket, etc. A person's average exposure depends upon the sources they encounter, how close they are to them, and the amount of time they spend there.[68] As stated above, the average exposure to magnetic fields in the U.S. is estimated to be around one mG or 0.1 µT, but can vary considerably depending on a person's exposure to EMF from electrical devices and wiring.[69] At times we are often exposed to much higher ELF magnetic fields, for example when standing three feet from a refrigerator the ELF magnetic field is 6 mG and when standing three feet from a microwave oven the field is about 50 mG.[70] The strength of these fields diminish quickly with distance from the source, but when surrounded by electricity in our homes and other buildings moving away from one source moves you closer to another. However, unless you are inside of the fence at a utility-scale solar facility or electrical substation it is impossible to get very close to the EMF sources. Because of this, EMF levels at the fence of electrical substations containing high voltages and currents are considered "generally negligible".[71, 72]

The strength of ELF-EMF present at the perimeter of a solar facility or near a PV system in a commercial or residential building is significantly lower than the typical American's average EMF exposure.[73, 74] Researchers in Massachusetts measured magnetic fields at PV projects and found the magnetic fields dropped to very low levels of 0.5 mG or less, and in many cases to less than background levels (0.2 mG), at distances of no more than nine feet from the residential inverters and 150 feet from the utility-scale inverters.[75] Even when measured within a few feet of the utility-scale inverter, the ELF magnetic fields were well below the International Commission on Non-Ionizing Radiation Protection's recommended magnetic field level exposure limit for the general public of 2,000 mG.[76] It is typical that utility scale designs locate large inverters central to the PV panels that feed them because this minimizes the length of wire required and shields neighbors from the sound of the inverter's cooling fans. Thus, it is rare for a large PV inverter to be within 150 feet of the project's security fence.

Anyone relying on a medical device such as pacemaker or other implanted device to maintain proper heart rhythm may have concern about the potential for a solar project to interfere with the operation of his or her device. However, there is no reason for concern because the EMF outside of the solar facility's fence is less than 1/1000 of the level at which manufacturers test for ELF EMF interference, which is 1,000 mG.[77] Manufacturers of potentially affected implanted devices often provide advice on electromagnetic interference that includes avoiding letting the implanted device get too close to certain sources of fields such as some household appliances, some walkie-talkies, and similar transmitting devices. Some manufacturers' literature does not mention high-voltage power lines, some say that exposure in public areas should not give interference, and some advise not spending extended periods of time close to power lines.[78]

# 3. Electric Shock and Arc Flash Hazards

There is a real danger of electric shock to anyone entering any of the electrical cabinets such as combiner boxes, disconnect switches, inverters, or transformers; or otherwise coming in contact with voltages over 50 Volts.[79] Another electrical hazard is an arc flash, which is an explosion of energy that can occur in a short circuit situation. This explosive release of energy causes a flash of heat and a shockwave, both of which can cause serious injury or death. Properly trained and equipped technicians and electricians know how to safely install, test, and repair PV systems, but there is always some risk of injury when hazardous voltages and/or currents are present. Untrained individuals should not attempt to inspect, test, or repair any aspect of a PV system due to the potential for injury or death due to electric shock and arc flash, The National Electric Code (NEC) requires appropriate levels of warning signs on all electrical components based on the level of danger determined by the voltages and current potentials. The national electric code also requires the site to be secured from unauthorized visitors with either a six-foot chain link fence with three strands of barbed wire or an eight-foot fence, both with adequate hazard warning signs.

# 4. Fire Safety

The possibility of fires resulting from or intensified by PV systems may trigger concern among the general public as well as among firefighters. However, concern over solar fire hazards should be limited because only a small portion of materials in the panels are flammable, and those components cannot self-support a significant fire. Flammable components of PV panels include the thin layers of polymer encapsulates surrounding the PV cells, polymer backsheets (framed panels only), plastic junction boxes on rear of panel, and insulation on wiring. The rest of the panel is composed of non-flammable components, notably including one or two layers of protective glass that make up over three quarters of the panel's weight.

Heat from a small flame is not adequate to ignite a PV panel, but heat from a more intense fire or energy from an electrical fault can ignite a PV panel.[80] One real-world example of this occurred during July 2015 in an arid area of California. Three acres of grass under a thin film PV facility burned without igniting the panels mounted on fixed-tilt racks just above the grass.[81] While it is possible for electrical faults in PV systems on homes or commercial buildings to start a fire, this is extremely rare.[82] Improving understanding of the PV-specific risks, safer system designs, and updated fire-related codes and standards will continue to reduce the risk of fire caused by PV systems.

PV systems on buildings can affect firefighters in two primary ways, 1) impact their methods of fighting the fire, and 2) pose safety hazard to the firefighters. One of the most important techniques that firefighters use to suppress fire is ventilation of a building's roof. This technique allows superheated toxic gases to quickly exit the building. By doing so, the firefighters gain easier and safer access to the building, Ventilation of the roof also makes the challenge of putting out the fire easier. However, the placement of rooftop PV panels may interfere with ventilating the roof by limiting access to desired venting locations.

New solar-specific building code requirements are working to minimize these concerns. Also, the latest National Electric Code has added requirements that make it easier for first responders to safely and effectively turn off a PV system. Concern for firefighting a building with PV can be reduced with proper fire fighter training, system design, and installation. Numerous organizations have studied fire fighter safety related to PV. Many organizations have published valuable guides and training programs. Some notable examples are listed below.

- The International Association of Fire Fighters (IAFF) and International Renewable Energy Council (IREC) partnered to create an online training course that is far beyond the PowerPoint click-and-view model. The self-paced online course, "Solar PV Safety for Fire Fighters," features rich video content and simulated environments so fire fighters can practice the knowledge they've learned. www.iaff.org/pvsafetytraining
- Photovoltaic Systems and the Fire Code: Office of NC Fire Marshal
- Fire Service Training, Underwriter's Laboratory

- Firefighter Safety and Response for Solar Power Systems, National Fire Protection Research Foundation
- Bridging the Gap: Fire Safety & Green Buildings, National Association of State Fire Marshalls
- Guidelines for Fire Safety Elements of Solar Photovoltaic Systems, Orange County Fire Chiefs Association
- Solar Photovoltaic Installation Guidelines, California Department of Forestry & Fire Protection, Office of the State Fire Marshall
- PV Safety & Firefighting, Matthew Paiss, Homepower Magazine
- PV Safety and Code Development: Matthew Paiss, Cooperative Research Network

# Summary

The purpose of this paper is to address and alleviate concerns of public health and safety for utility-scale solar PV projects. Concerns of public health and safety were divided and discussed in the four following sections: (1) Toxicity, (2) Electromagnetic Fields, (3) Electric Shock and Arc Flash, and (4) Fire. In each of these sections, the negative health and safety impacts of utility-scale PV development were shown to be negligible, while the public health and safety benefits of installing these facilities are significant and far outweigh any negative impacts.

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# Thin-Film CdTe Photovoltaic Technology Scientific Review

## Assessing the impacts and benefits of First Solar's CdTe technology for large scale deployment in Brazil: performance, environmental health and safety

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# Executive Summary

Photovoltaic solar energy conversion (PV) is the direct conversion of sunlight into electricity. PV is currently the fastest-growing energy technology worldwide [1], and there are a number of different PV technologies in the market. With the tremendous cost-reductions experienced by this industry in recent years, PV generation has consistently grown at nearly 55%/year over the last five years, and is becoming cost-competitive with many of the conventional and large-scale electricity generation technologies. Among the commercially-available PV technologies, thin-film Cadmium Telluride (CdTe) has demonstrated consistent year-on-year developments in both cost-reduction and efficiency improvements.

This scientific review of the *CdTe photovoltaic (PV) technology: Impacts and benefits of First Solar's CdTe technology for large-scale deployment in Brazil including the performance, environmental, health and safety assessment,* covers issues related to both the large-scale manufacturing and large-scale field deployment of thin-film CdTe PV devices in grid-connected power plants in Brazil[1]. An extensive and independent review of the published literature was carried out in order to assess whether the production and use of CdTe PV modules and systems introduces environmental, health or safety risks to individuals under normal operating conditions and foreseeable accidents at any stage of fabrication, transportation, installation, utilization, decommissioning or recycling. The review includes information obtained from publicly available literature and studies carried out by third parties, information obtained directly from CdTe PV module manufacturer First Solar, as well as information gathered during a site visit to First Solar's manufacturing plant in Perrysburg-OH in the USA in September 2014.

Compared with other PV technologies available in the market, the lower temperature coefficient of power of CdTe PV renders it a better performer under the high operating temperatures prevailing in the field, especially in warm and sunny countries like Brazil. The study also compares the potential deployment of large-scale CdTe solar power plants with the most relevant commercially-available PV technologies, as well as with other more conventional electricity generation technologies, with emphasis on large-scale hydropower generation. Hydroelectricity generation is by far the major source

[1] Worldwide, utility-scale PV (i.e., power plants larger than 5 MWp) has been the fastest-growing sector of the PV market since 2007, and since 2012 has accounted for the largest share of the overall PV market in terms of new MWp installed [http://emp.lbl.gov/reports/re]. In Brazil, utility-scale solar PV generation is only now getting started, with the first of the so-called solar auctions carried out by the Brazilian government on 31st October 2014. In this first solar auction, a total of 31 solar farms, with a total nominal capacity of 1,048 MWp of PV, were contracted.

of electricity in Brazil (> 70%), and electricity consumption in the country has increased more than 5%/year over the last 40 years, reaching 473 TWh in 2014 [2]. The report shows that despite being area-intensive, PV power plants can generate more electricity per occupied area than large hydropower plants operating in Brazil[2]. The Itaipu[3] hydropower plant is an emblematic example of how well PV generation compares with hydroelectricity production in terms of land use. If the 1,350 km$^2$ surface area of the Itaipu lake were covered with 15% efficient CdTe First Solar[4] PV modules side by side, this gigantic PV plant would be rated at over 200 GWp (instead of the 14GW nominal power of the Itaipu hydropower plant), and would be able to generate over 240 TWh/year under the irradiation conditions where Itaipu is located. Furthermore, if the 40,000 km$^2$ of all the Brazilian hydropower plant flooded areas combined were covered with 15% efficient PV modules side by side, the total installed PV capacity would be close to 6 TWp (6,000 GWp). If a conservative average annual PV energy generation yield of 1,200 kWh/kWp/year is assumed for the combined regions where all these hydropower plants operate, around 7,200 TWh of solar electricity could be produced annually. This is over ten times more than the current annual electricity consumption in Brazil, more than what was consumed in the USA (4,274 TWh in 2013) or China (5,023 TWh in 2013), and around one third of all the annual electricity consumption of the whole planet [2]! These impressive figures are presented to give a rough idea of the potential of PV solar power plants in Brazil, and compared with the total accumulated installed PV capacity on the whole planet (reaching close to 170 GWp at the end of 2014), demonstrate that despite its huge potential, there is still a long way until a more widespread use of PV technology results in solar electricity becoming a major contributor to the Brazilian or worldwide energy mix. One last comparison that can be made between hydropower and solar power generation in Brazil is related to the complementary nature of the water and solar resource availability (e.g., high solar irradiation in times of draught). Many of the large Brazilian hydropower plants are seasonally water constrained, depending on the particular year's rain pattern, whereas PV requires little to no water to operate [3,4]. 2014 brought the first national energy auction with a specific category for solar power, and also the worst draught in eight decades in the Brazilian Southwest. The combined impulse of these two events can make 2014 a turning point for solar PV development in Brazil: results of the first solar auction held in the country, which contracted

[2] More than 10% of the total world installed hydropower capacity of some 1,000 GW are installed in Brazil. The total flooded areas of these 104 GW of hydropower operating in Brazil is in excess of 40,000 km$^2$ (http://www.aneel.gov.br/aplicacoes/capacidadebrasil/energiaassegurada.asp).

[3] Until 2014, the Itaipu (14 GW generating capacity) dam in Brazil used to be the largest hydropower plant in the world in terms of annual electricity generation. While the Three Gorges (22 GW installed capacity) hydropower plant in China has a larger nominal rating, it has historically been the second largest operating hydroelectric facility in terms of annual energy generation, generating 98.1 TWh in 2012 and 83.7 TWh in 2013, while the annual energy generation of the Itaipu dam was 98.3 TWh in 2012 and 98.6 TWh in 2013 http://www.mme.gov.br/mme/galerias/arquivos/noticias/2014/Energia_no_Mundo_-_OIE_e_OIEE_-_Final.pdf. In 2014, due to unfavorable hydrological conditions, it was anticipated that Itaipu would lag behind Three Gorges.

[4] This report is based on 15% efficient First Solar Series 4 PV modules, released in 2014.

the first batch of large-scale PV solar plants in Brazil (total of 1,048 MWp) were announced on the same day when Itaipu Hydropower released information that, due mostly to water constraints, the largest Brazilian power plant has generated less electricity in 2014 than in previous years[5].

The carbon footprint of CdTe PV generation ($CO_2$ equivalent per MWh generated), as well as the Energy Pay-Back Time (EPBT) of CdTe PV are also presented in the study, and compared with other commercially-available PV technologies, as well as with large hydropower electricity production in Brazil. The EPBT is measured in years and represents the time a CdTe PV module or system should operate in the field in order to produce the amount of energy equivalent to fabricate the PV module or system. The lifetime $CO_2$-equivalent emission of a CdTe PV plant operating in Brazil is around 0.01 $tCO_2$/MWh (10 $gCO_2$/kWh), which is orders of magnitude lower than any of the current conventional electricity sources, including the Brazilian hydropower-dominated electricity generation mix [5-7]. A hydropower dam emits biogenic gases such as $CO_2$ and mostly $CH_4$, which is a powerful greenhouse gas (according to the IPCC, $CH_4$ is 25 to 72 times stronger a heat-trapping gas than $CO_2$, depending on the timeframe considered [8]). The amount of energy that a CdTe PV module or power plant will be able to generate in Brazil over its +25 years lifetime is up to 30 times larger than the energy required to produce that same PV module or solar power plant. The typical EPBT of CdTe in Brazil is shorter than one year, ranging from 0.82 to 0.94 years in the regions where utility-scale solar power plants will be installed, and 1.22 years at the least sunny sites in the country. Mono and multi-crystalline silicon PV modules operating in Brazil will also present a considerably larger carbon footprint (ranging from 30 to over 60 $gCO_2$/kWh) and EPBT (ranging from 1.82 to 3.07 years) than CdTe PV.

Heavy metal emissions is a sensitive topic, and the environmental, health and safety review also addresses this important issue, with extensive literature showing that CdTe is a solid and stable compound that is insoluble in water, is far less toxic than elemental Cd [9,10], and does not vaporize at the temperatures likely to be reached even if CdTe PV modules are exposed to a typical field fire. The European Chemical Agency (ECHA) does not classify CdTe as harmful if ingested or if in contact with skin, and CdTe PV modules pass the U.S. EPA's Toxicity Characteristic Leaching Procedure (TCLP) test, designed to assess the potential for long-term leaching of products disposed in landfills [11,12]. At end-of-life, discarded CdTe PV modules from solar power plants in Brazil should not be characterized as hazardous waste, if they are not finally disposed of in Brazil (e.g. transported outside of Brazil for recycling)[6]. In 2005 First Solar established a global and comprehensive

[5] http://www1.folha.uol.com.br/mercado/2014/11/1541888-itaipu-perde-lideranca-em-energia.shtml

[6] Under Brazilian law, waste containing Pb or Cd is listed as hazardous waste regardless of the volume of the chemical it contains (Brazilian Association of Technical Standards - *ABNT* by means of the normative *NBR*

collection and recycling program, in which over 90% of the semiconductor material and around 90% of the glass is currently recycled in facilities located in the USA, Germany, and Malaysia. With larger volumes, which are likely in future volume markets like Brazil, First Solar expects to reduce the transportation costs of the recycling process, and run mobile or in-country recycling facilities as a profitable part of the PV manufacturing business.

First Solar's efficiency roadmap has led to fleet average, best line average, and record PV module efficiencies of 15.4%, 16.2% and 18.6%, respectively through mid-2015, with prospects for more than 20% efficiencies in the near future, and close to 25% as a possible limit. Considering the better spectral response to the bluer spectra resulting from more humid climates, and the low temperature coefficient of power of CdTe (-0.25 to -0.34%/$^{o}$C, compared with -0.45 to -0.50%/$^{o}$C for crystalline silicon PV), the effective power conversion efficiency of CdTe at the higher operating temperatures prevailing in the field in Brazil is higher than that of the conventional silicon PV technologies. This will lead to more energy (kWh = revenue) generated for each unit of power (kWp = investment) installed.

The overall conclusion of this study is that CdTe PV is one of the most adequate solar energy generation technologies for the Brazilian climatic conditions, and that CdTe PV systems do not represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product, including recycling. CdTe PV provides a good combination of large-scale industrial processing and field performance, making it a cost-effective technology for utility-scale PV plants in Brazil. Expected efficiency improvements and cost-reductions shown in First Solar's roadmaps are likely to consolidate this position.

10004:2004). Since Pb and/or Cd compounds are commonly used in commercial PV modules including silicon PV [9], these modules are likely to be characterized as hazardous waste at end-of-life if disposed of in Brazil.

# 1. Introduction

Solar electricity or solar PV generation is the static and direct conversion of the photon energy contained in sunlight into electrical energy, with no moving parts, no noise and no emissions into the air. The photovoltaic effect was first reported in 1839 by French physicist A-E. Becquerel, but the first practical PV device designed for energy conversion was a silicon solar cell presented in 1954 by researchers from the Bell Telephone Laboratories in the USA, with a 6% conversion efficiency [13]. In 1958 the first solar cells went to space powering the US satellite Vanguard I [14]. Vanguard I was the fourth artificial satellite to be sent to orbit, and at that time satellites were equipped with primary batteries that would discharge and disable communication with Earth after a few weeks in space. The robustness and reliability of PV cells in space resulted in Vanguard I communicating with Earth for over 10 years, and this event has set the stage for photovoltaics powering most of the satellites orbiting our planet to date.

While PV has the potential of becoming a major source of renewable and sustainable electricity generation worldwide, this potential can only be realized if PV devices that will operate reliably in the field for 25-30 years can be mass-produced in square-kilometers per year, and at costs below US$ 100/m$^2$ [15]. In the 60 years that passed since the early days of > US$ 1000/m$^2$, cm$^2$-area single-cell PV devices that could only be afforded in space applications, to modern, < US$ 100/m$^2$, m$^2$-area PV modules for bulk-power production in terrestrial applications, considerable R&D efforts and budgets were involved. R&D on a considerable number of materials for solar cell device production, and on large-scale, large-throughput industrial processes was also carried out extensively worldwide, resulting in PV finally starting to become cost-competitive in a number of markets worldwide. Finally, on top of all the issues related to reliability, volumes and cost, PV will only be a truly sustainable and viable energy generating technology if all processes involved in producing, transporting, installing, operating, decommissioning and recycling of solar PV plants are associated with acceptable environmental, health and safety impacts.

## 1.1. Purpose and scope

First Solar has participated in 12 Peer Review Studies since 2003 [16-27], where specialists from the USA (2003), the European Union (2005), France (2009), Spain (2010), Japan (2012), Germany (2012), Italy (2012), India (2012), Thailand (2012), the Middle East (2012), China (2013) and Chile (2013) were invited to carry out literature reviews on the potential impacts of large-scale deployment of the thin-film CdTe PV technology. This study aims at presenting an independent overview of the thin-film CdTe PV technology currently produced by First Solar, assessing the performance aspects, and the Environmental, Health and Safety (EHS) aspects of CdTe PV systems over their entire lifecycle, including issues related to the carbon footprint of CdTe PV production and deployment, and the Energy Pay-Back Time (EPBT) of this thin-film solar PV technology. The report briefly presents the world PV market and the commercially-available PV technologies, and then describes First Solar's CdTe PV module production technology and cost roadmap. The literature review includes a comprehensive but concise study on raw materials, manufacturing and recycling processes involved in CdTe PV module production at First Solar. The report also addresses output performance aspects of CdTe PV generation vis-à-vis the more traditional and commercially-available solar PV technologies in a sunny and warm climate, and finally, it compares land use and greenhouse gas (GHG) emissions of CdTe PV generation with the large hydropower generation plants operating in Brazil.

## 1.2. The solar PV market: Commercially-available PV technologies for terrestrial applications

The commercial PV scene has always been dominated by bulk single (or mono) and multicrystalline silicon devices [28], and thin-film CdTe is currently one of the most serious competitors in terms of efficiency and production costs. Thin-film solar cells present basic advantages over their bulk crystalline counterparts in terms of materials utilization, mass production and integrated module fabrication, and this has been the driving force for their development since the early sixties [28]. For thin-film PV devices, of the many materials and device configurations studied, three material families have emerged and reached industrial production and commercialization: (i) amorphous and microcrystalline silicon alloys (a-Si and µc-Si); (ii) cadmium telluride-based devices (CdTe); and solar cells based on copper, indium, gallium and selenium ($CuInGaSe_2$ or CIGS). These thin-film material families constitute the so-called second-generation PV technologies. Third-generation PV cells include organic, Perovskite, quantum dot and photoelectrochemical solar cells at different stages of R&D and pilot production, but so far only the first-generation bulk crystalline silicon and the three above-mentioned second-generation PV technologies are commercially available in large-area, large-scale production.

There is a multitude of PV materials and technologies at different stages of R&D, pilot and commercial production worldwide. Figure 1 shows a classical chart created and regularly updated by researchers at the National Renewable Energy Laboratory in the USA, which includes all PV technologies' best research-cell efficiencies. Of immediate interest for terrestrial, utility-scale applications are the blue and green families of data points. Solid and open blue squares represent respectively the more traditional single and multicrystalline silicon PV technologies, which together accounted for 90% of the worldwide 2014 PV shipments of some 40 GWp. Green circles represent the thin-film PV technologies: a-Si and µc-Si; CdTe; and CIGS. Among these thin-film technologies, market share in 2014 was 23% for a-Si and µc-Si; 23% for CIGS, and 54% for CdTe. Figure 2 shows the evolution of the global PV market from 1997 to 2014. Figures 3 and 4 show respectively the evolution of the market share among these first- and second-generation PV technologies from the early 1980's, and the evolution of the market share among the thin-film PV technologies since the year 2000.

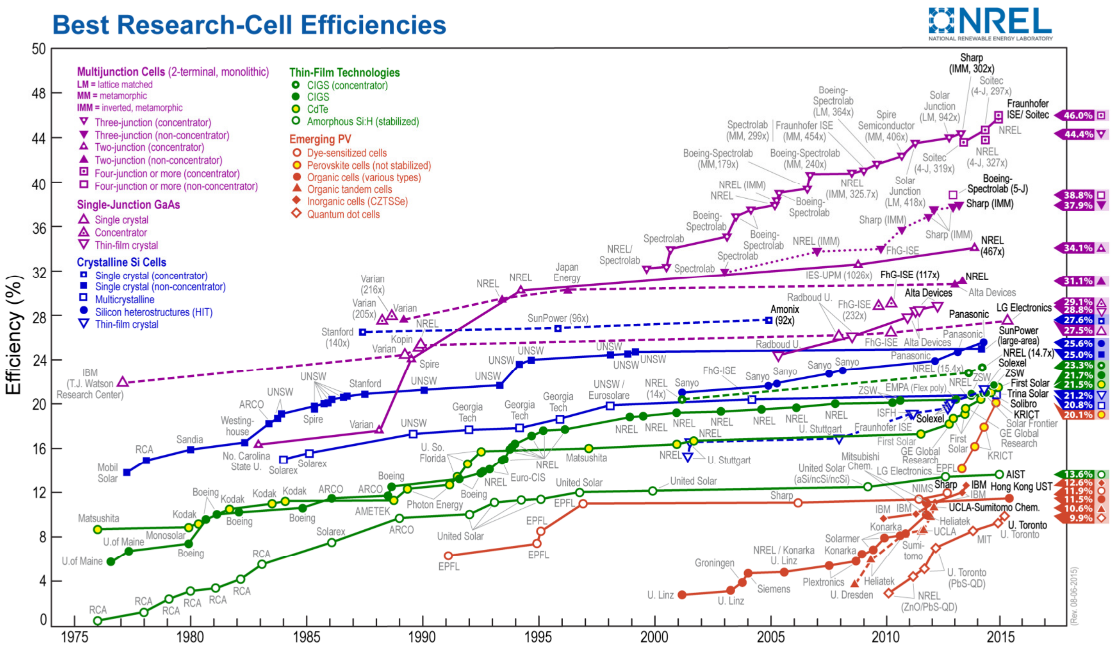


Figure 1: The National Renewable Energy Laboratory – NREL's solar cell efficiency chart [29] showing the evolution of the best research-cell efficiencies since the 1970's (updated June 2015).

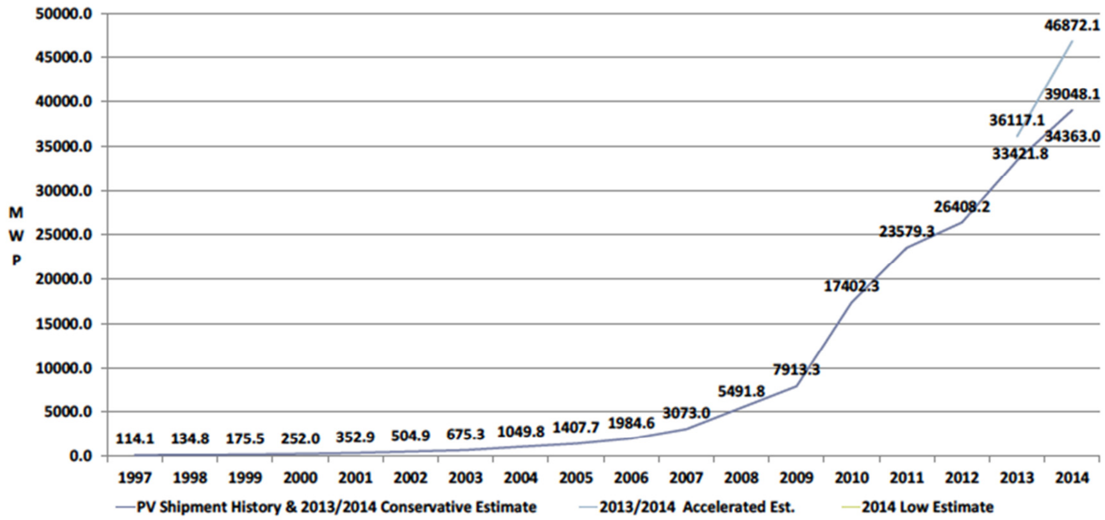


Figure 2: Global PV shipments from 1997 to 2014 [30]. With the PV incentive programs that were started with the establishment of the German feed-in tariff in the early 2000's, the global PV market reached the necessary scale for an effective cost-reduction that is still in course.

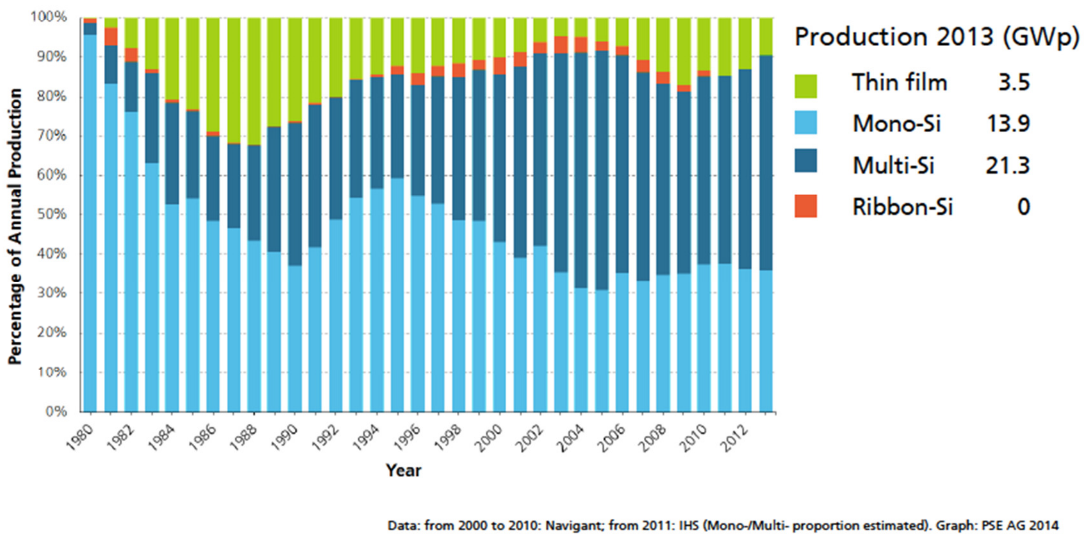


Figure 3: Evolution of the market share of first- and second-generation PV technologies from the early 1980's [31].

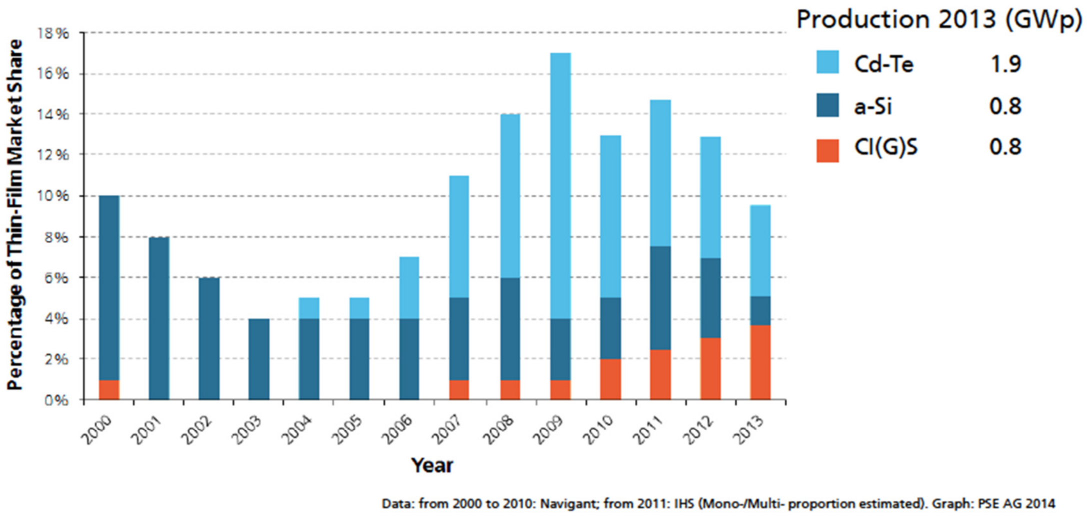


Figure 4: Evolution of the market share of second-generation thin-film PV technologies from the year 2000 [31].

Second-generation, or thin-film PV solar cells are typically a glass-glass laminate, with a very thin layer of active semiconductors, metal and oxide contacts sandwiched between these two glass panes. First Solar's thin-film solar cell structure is shown in Figure 5.

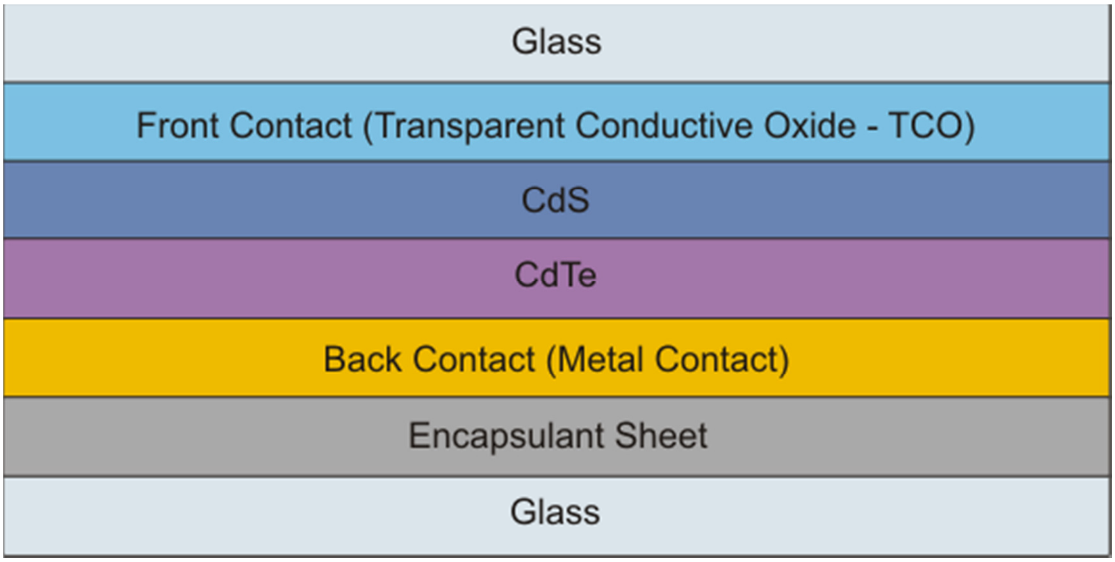


Figure 5: Schematic structure (layer thicknesses not to scale) of First Solar's thin-film CdTe PV devices, showing the active CdTe and CdS semiconductors, and metal and oxide (back and frontal) contacts sandwiched between two sheets of glass.

Research in CdTe dates back to the 1950's, after it was established that its band gap (~1.5 eV) almost perfectly matched to the distribution of photons in the solar spectrum in terms of conversion to electricity. A simple heterojunction design evolved in which p-type CdTe was matched with n-type CdS [32]. The cell was completed by adding top and bottom contacts. Early leaders in CdS/CdTe cell efficiencies were GE in the 1960's, and then Kodak, Monosolar, Matsushita, and AMETEK. In Europe, the development of thin-film CdTe solar cells started with the 6% efficient CdTe/CdS device presented by Bonnet and Rabenhorst in 1972 [33]. Much R&D was carried out to reach the present champion efficiency of 21.5% for a small-area single-cell device, and a 18.6% efficient full-size (0.72 $m^2$), 216-cell monolithic CdTe PV module, both produced by First Solar and independently confirmed [34]. The theoretical efficiency for a single junction CdTe/CdS solar cell is 33% [35]. Commercially-available CdTe is presently at the same efficiency level as multicrystalline silicon, and has the potential of reaching and even surpassing monocrystalline silicon efficiency levels in the future[7].

### 1.2.1. Temperature effects on PV system performance

All PV devices suffer output performance losses with increasing operating cell temperatures in the field. The negative temperature coefficient of power ($T_{coeff}P_{max}$) of first- and second-generation PV devices is shown in Table 1,

[7] R. Garabedian, "Technology Update," First Solar Analyst Meeting, 2014.

and the negative effects of field operating temperatures on power output are shown in Figure 6.

Table 1: The temperature coefficient of power (TcoeffPmax) of first- and second-generation PV devices (adapted from [36]).

| PV Technology | bulk Si | a-Si/μc-Si | CIGS | CdTe[8] |
|---|---|---|---|---|
| $T_{coeff}P_{max}$, %/°C | -0.41 to -0.57 | -0.10 to -0.30 | -0.36 to -0.50 | -0.25 to -0.34 |

For a maximal operating PV cell temperature of 65°C in the field, the temperature losses for a CdTe PV power plant will be in the order of 10%, while the crystalline silicon temperature losses will be around 18%.

Conversion efficiency is directly related to a PV power plant footprint, which is particularly important in utility-scale PV as it relates to land use, metallic support structures for ground-mounting of PV arrays, and copper wiring, which are part of the so-called Balance-of-Systems (BOS) costs. With the fast declining costs of PV modules, BOS costs are becoming dominant, and the current 15% efficiency of First Solar's CdTe, along with its low temperature coefficient on power, result in the same effective conversion efficiency level as that of multicrystalline silicon devices for operation in warm climates like Brazil.

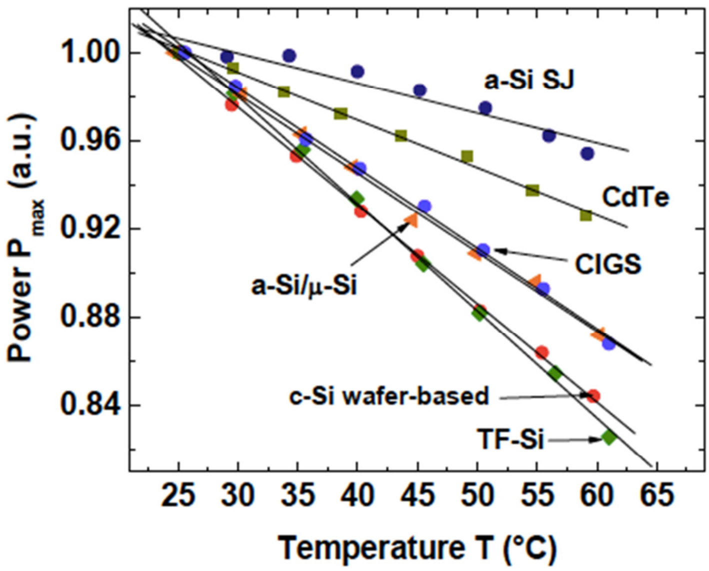


Figure 6: The negative effect of operating cell temperatures on the output power of first- and second-generation PV technologies [36].

[8] In 2015, Series 4-2 First Solar PV modules will be commercially available with higher efficiency, but slightly higher temperature coefficient: -0.34%/°C.

### 1.2.2. Spectral effects on PV system performance

For first- and second-generation PV technologies, the conversion efficiency of a solar cell device is also dependent on the energy bandgap of the corresponding semiconductor material, and different semiconductors will "see" different portions of the solar spectrum. Figure 7 shows the external quantum efficiency curves for a number of PV technologies, which translates into the device's spectral response. While crystalline silicon and thin-film CIGS PV have a spectral response that spans from 380 nm to around 1180 and 1280 nm respectively (they are "redder" PV devices), thin-film a-Si responds to light in the 360 nm to 790 nm range, and thin-film CdTe will be able to convert into electricity photons in the range from 280 nm to 900 nm. Thin-film a-Si and CdTe are therefore "bluer" solar cell devices than crystalline silicon and CIGS, and will perform better in climates with higher cloud cover levels, which lead to a blue-shifted spectrum. The Standard ASTM G173-03 spectrum was derived based on the spectral distribution of sunlight for a number of high direct normal irradiation level North American locations (DNI levels averaging 2410 kWh/m$^2$/year and ranging from 2190 to 2740 kWh/m$^2$/year), where clear skies are predominant, and Aerosol Optical Depths – AOD levels are low. These sites present a much "redder" spectral distribution of sunlight than what is typically found in Brazilian locations, where the presence of different levels of cloud cover lead to a "bluer" spectral distribution. Figure 8 shows the spectral content of sunlight at latitude tilt in Petrolina-PE (latitude 9$^o$23" South), a typical warm and sunny Brazilian Northeast site, in comparison with the Standard ASTM G-173 spectrum. Figure 9 shows, for four Brazilian locations spanning from North to South and West to East, the deviation from the ASTM G-172 spectrum, and it can be seen that the spectral distribution of sunlight at all four Brazilian sites contains more blue photons and less red photons than the Standard ASTM G-173 spectrum. Thus, it can be inferred that, from a spectral content perspective, CdTe PV should be a good performance at these sites.

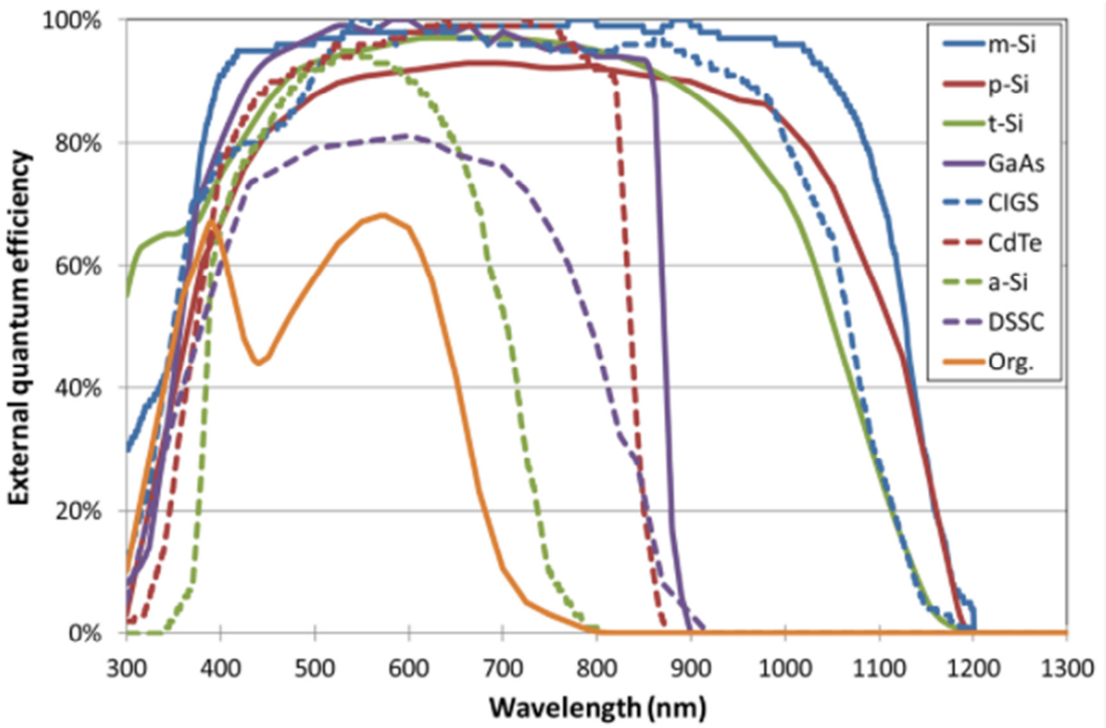


Figure 7: External quantum efficiency curves for a number of solar cell materials. The more shifted to the left (lower wavelengths) a curve is, the better the corresponding material will respond to a blue-shifted spectral content of light [37].

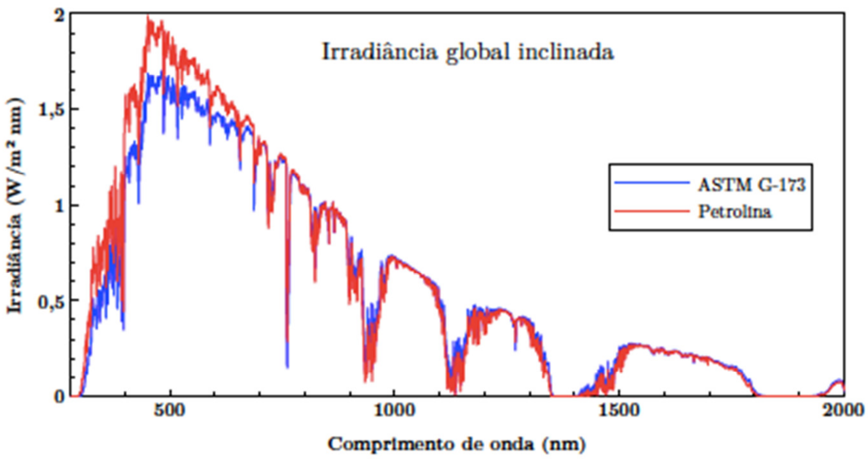


Figure 8: Spectral distribution of sunlight at the Brazilian site Petrolina-PE (latitude = 9o23" South), in comparison with the Standard ASTM G-173 spectrum, showing the higher level of irradiance at lower (bluer) wavelengths at latitude tilted planes [38].

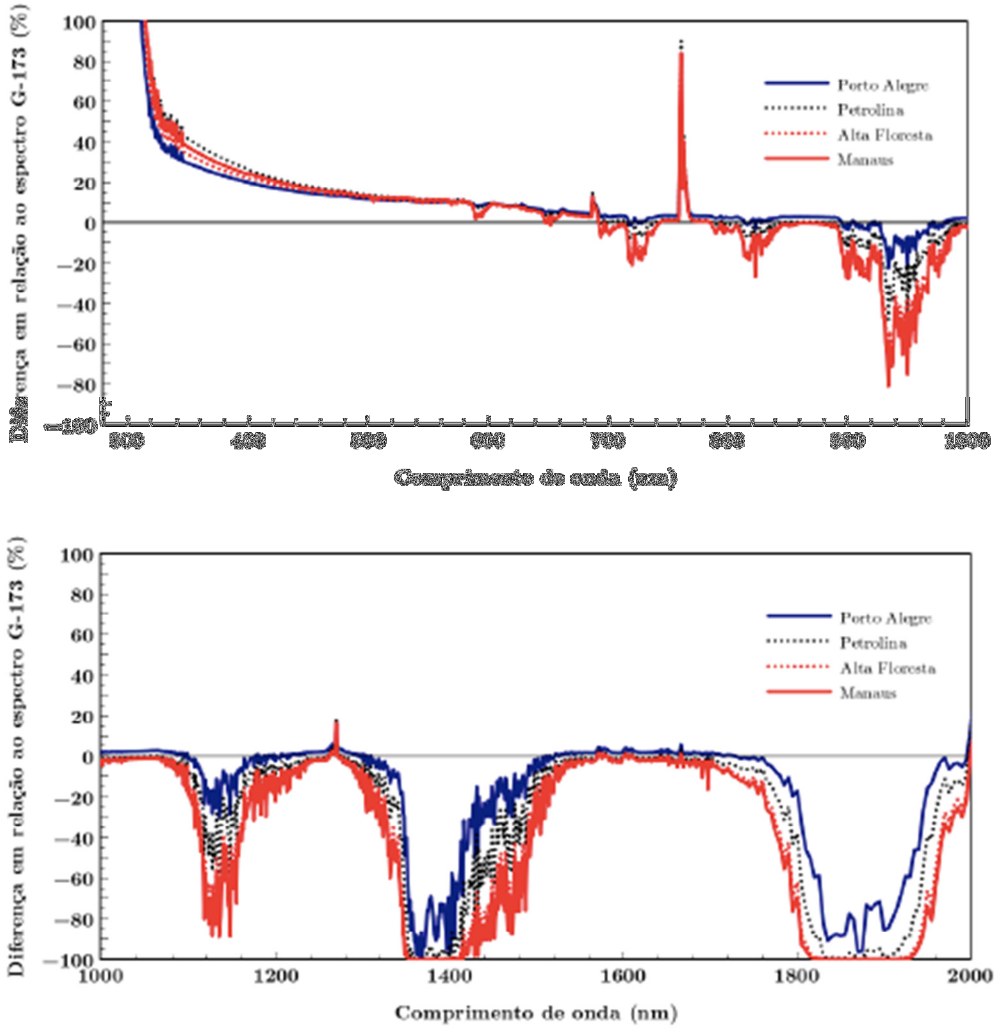


Figure 9: Relative difference between the spectral content of sunlight at four Brazilian sites, and the Standard ASTM G-173 spectrum, showing that the four locations have a spectral distribution that has more blue and less red photons than the standard spectrum [38].

Among the commercially-available PV technologies, thin-film CdTe presents a good combination of high efficiency, low temperature coefficient ($T_{coeff}P_{max}$), and spectral response match with the spectral content of sunlight at Brazilian sites. It is expected that this technology will present a superior performance in terms of kWh generated (= revenue) per installed kWp (= investment) in Brazil.

## 1.3. First Solar's CdTe thin-film PV technology, efficiency and cost roadmap

First Solar was founded in 1999 after acquiring Solar Cells Inc, and was the first PV manufacturer to produce 1 GWp of solar modules in a single year, and to break the US$ 1/Wp manufacturing cost barrier (US$ 0.63/Wp in 2013[9]). First Solar was also the first PV manufacturer to implement a global PV module recycling program in 2005. The basic First Solar PV product is a 12 kg, frameless, glass-glass 60 cm x 120 cm laminate, where a number (currently 216) of monolithically-integrated CdTe/CdS semiconductor PV cells are sandwiched between a 3.2 mm heat strengthened front glass and a 3.2 mm tempered back glass. On that same 0.72 $m^2$ surface area, 2004 vintage PV modules were rated at 45Wp (6.25% conversion efficiency), and today PV modules with up to 110Wp (15.28% conversion efficiency) at Standard Test Conditions – STC[10] are currently available (Q1-2015).

On top of developing its own technology and manufacturing of CdTe solar modules, First Solar is also a solar power plant developer and contractor (3+ GWp contracted project pipeline in 2014) and currently operates more than 2 GWp of CdTe power plants, with an average system availability of over 99%[11]. The company is pioneering in the development of advanced grid integration, plant control and forecasting, and energy scheduling capabilities, aiming at integrating utility-scale solar PV into the global energy mix. In an effort to further reduce large-scale PV generation costs, First Solar has recently raised its maximum PV module voltage rating to 1500 V, which results in lower BOS costs. First solar has also concentrated its marketing efforts and strategic positioning on the PV market with a focus on utility-scale, multi-megawatt projects, and has successfully managed to build some of the largest PV projects so far. As Figure 10 shows, with the phasing out of feed-in incentive PV programs worldwide, the PV market is shifting from smaller and distributed residential rooftop PV generators, to more commercial, utility-scale solar power plants, where economies of scale continue to lead to consistent year-on-year cost reductions.

[9] T. de Jong, "Manufacturing Update," First Solar Analyst Meeting, 2014.
[10] STC are the Standard Test Conditions under which all PV modules are nameplate rated. These laboratory conditions include: Irradiance = 1000 W/m2; cell temperature = 25 °C, and spectral content of sunlight equivalent to AM 1.5
[11] T. Kuster, "System Technology Update," First Solar Analyst Meeting, 2013.
G. Antoun, "EPC, O&M and Market Segments," First Solar Analyst Meeting, 2014.

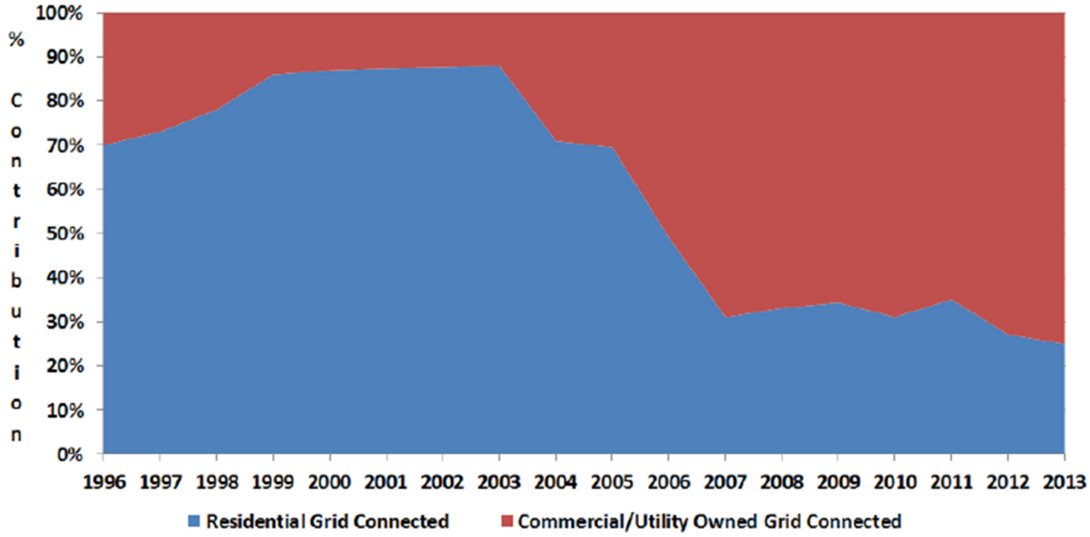


Figure 10: Evolution of the share between small-scale, residential grid-connected and utility-scale, multi-megawatt solar PV installations [39]. Large-scale currently represent more than 2/3 of the world PV market.

CdTe can be produced by a variety of technologies including closed-space sublimation (CSS), vapor transfer deposition (VTD), eletrodeposition, screen printing, plasma vapor deposition or sputtering among others [15,28]. First Solar processes its modules using high-rate vapor transfer deposition (VTD), which is similar to CSS (closed-space sublimation). The key is that the deposition rate of VTD is very high, and First Solar converts glass to module in less than 2.5 hours.

First Solar has owned and operated three CdTe PV module manufacturing and recycling facilities, namely in Perrysburg-OH, USA (PBG); Frankfurt-Oder, Germany (FFO); and Kulim, Malaysia (KLM). Figure 11 shows the total annual PV module production at each site and the total cumulative annual production. With the phasing out of the German feed-in incentive program, the German facility's manufacturing operations were interrupted in 2012, and the FFO plant currently hosts only First Solar's recycling activities. Through efficiency and throughput improvements, First Solar expects to have a combined annual manufacturing capacity of some 3500 MWp by 2018. First Solar dedicates about 25% of the PBG capacity to R&D and spends 4.5% of its revenue on R&D. At the end of 2013 First Solar was running each of the individual manufacturing lines at a Line Run Rate of 79 MWp/year, and at 0.63 US$/Wp manufacturing costs. R&D developments in back contact and anti-reflective coating led to an output of 89 MWp/year at year's end in 2014. Continuing R&D efforts forecast this figure to reach in excess of 130 MWp/year per individual line by the end of 2018, as shown in Figure 12.

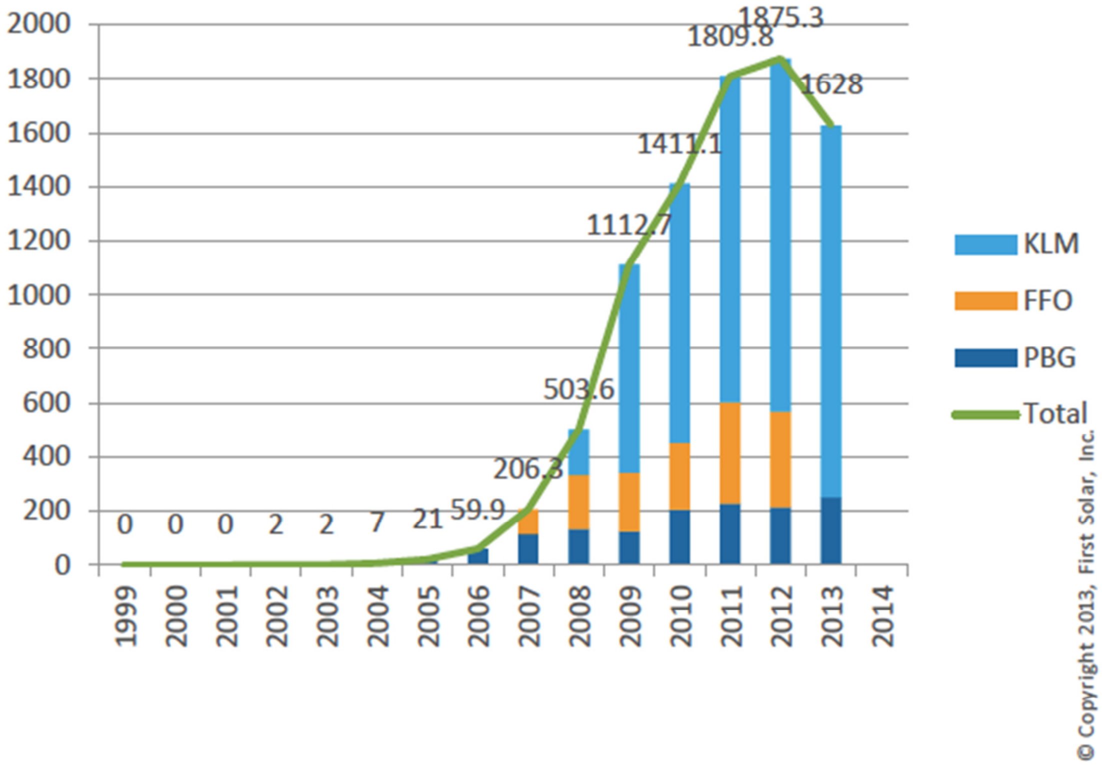


Figure 11: Annual PV module production (in MWpDC/year) for the three CdTe PV module manufacturing and recycling plants that First Solar runs in Perrysburg-OH (USA), Frankfurt-Oder (Germany) and Kulim (Malaysia).

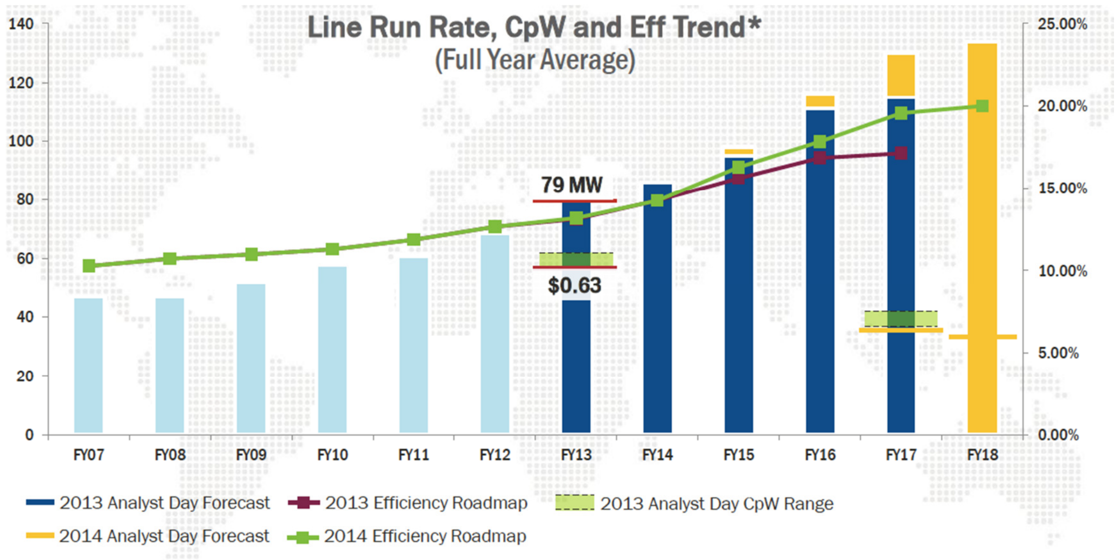


Figure 12: Annual increments in First Solar Line Run Rates, and the reviewed Efficiency Roadmap, with PV module efficiencies of 15% at the end of 2014, 20% in 2017-18.

The efficiency roadmap presented in Figure 13 shows First Solar's thin-film CdTe PV module improvements expected to lead to efficiencies approaching 20% by 2017-18. First Solar's PV module and PV systems cost roadmaps are qualitatively shown in Figure 14, as it is expected that efficiency increases should lead to production cost reductions. In 2017 First Solar expects CdTe PV system costs to drop to below the 1 US$/Wp mark.

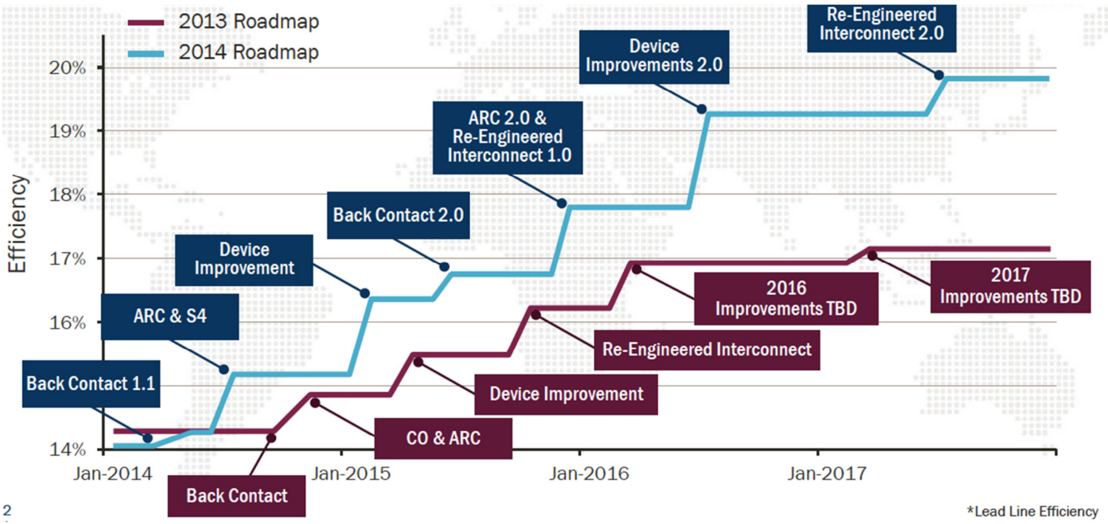


Figure 13: First Solar efficiency roadmap, showing the company's R&D strategies for CdTe PV module efficiency improvements in the period 2014-17.

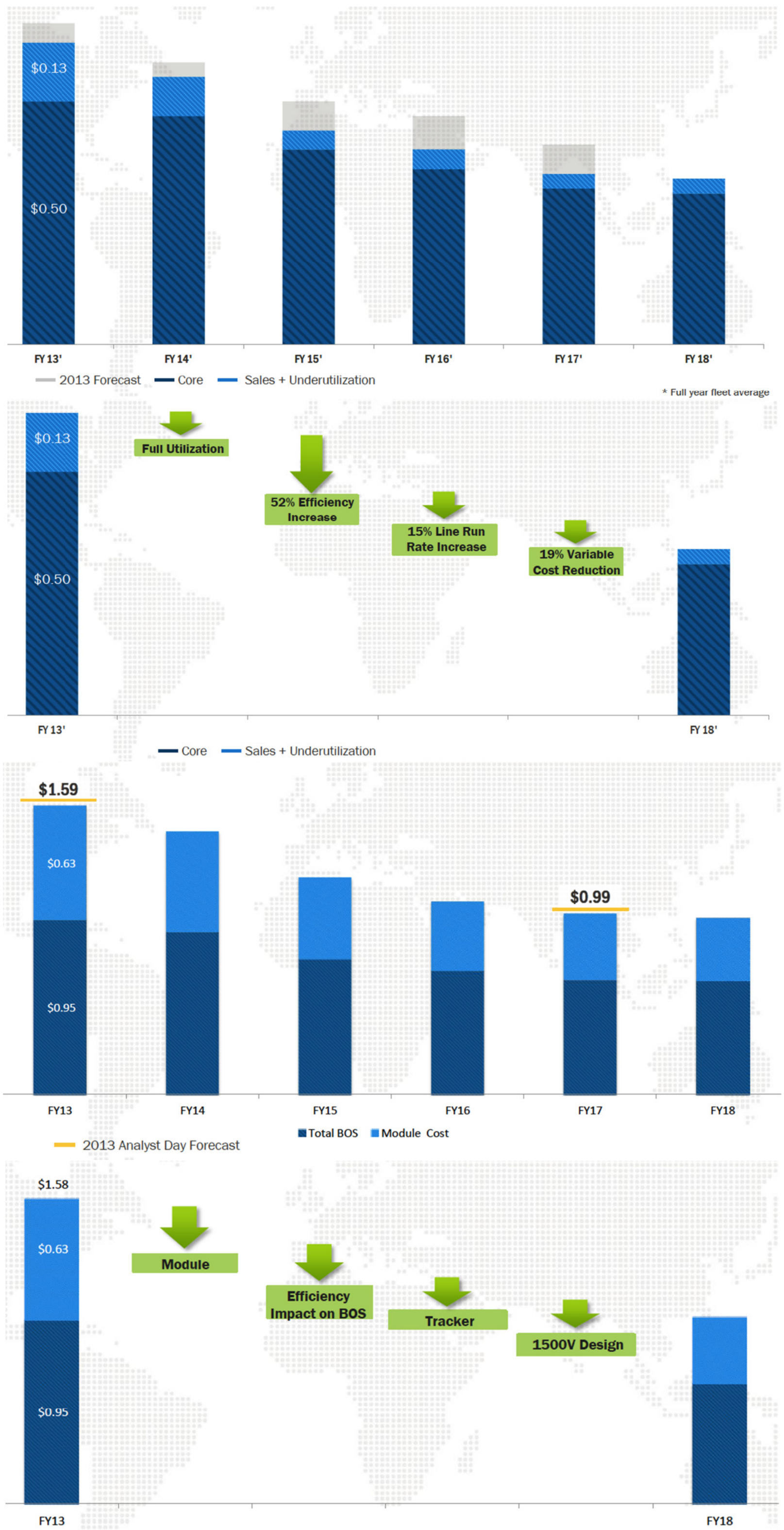


Figure 14: First Solar cost-reduction roadmap, showing the company's strategies for CdTe PV module (first and second charts) and solar power plant (third and fourth charts) cost reductions in the period 2014-18. In 2017 the company expects CdTe PV system costs to drop below the 1 US$/Wp mark.

The manufacturing processes used by First Solar in the production of CdTe PV modules are the same in all First Solar manufacturing plants around the globe, and the company adopted a so-called "Copy Smart" replication philosophy for quickly building new manufacturing facilities and minimize the risk of schedule, cost, environmental, health and safety issues, while guaranteeing product quality and uniformity. First Solar solar modules are identical wherever in the world they are manufactured, and new manufacturing lines operate with the same effectiveness as the base plant in Perrysburg in terms of costs, yields, and consistency. Continuous improvements achieved in any of the manufacturing plants can be realized and transferred quickly and globally after the concept has been proven at one location.

The next section presents a literature review on environmental, health and safety aspects of CdTe PV module production, transportation, utilization, decommissioning and recycling, showing the impacts and benefits of First Solar's solar generation technology for large-scale deployment in Brazil. The last section of this report presents issues related to the performance of PV in warm climates.

# 2. Literature review on Cadmium Telluride (CdTe)

## 2.1. Safety – Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product, including recycling?

Concerns have been raised about CdTe PV modules related to the heavy metal Cd, and the possibility of its release, either during module manufacture, transportation, deployment, decommissioning or recycling [15]. The lifecycle of CdTe includes: (i) Cd and Te mining as a by-product of the mining of Zn, Pb and Cu ores, and the smelting/refining of Zn, Pb and Cu; (ii) Cd and Te purification; (iii) CdTe production; (iv) manufacture of CdTe PV modules; (v) transportation, installation and commissioning, and deployment of CdTe PV modules in solar power plants; and (vi) decommissioning, transportation and recycling of CdTe PV modules at end-of-life.

Do CdTe PV systems represent an environmental, health or safety (EHS) risk under normal operating conditions and foreseeable accidents, up to the end of their lifetime? This section aims at presenting information to assist in answering this question, based on independent and bona fide data obtained from a representative sample of publicly-available reports and studies. While no direct or first-hand investigations were carried out on any of the aspects reported in this section, care was taken to present only information regarded as trustworthy. Some of the information presented on aspects of CdTe industrial production processes was obtained directly from First Solar, and a site visit to First Solar's manufacturing plant in Perrysburg-OH, USA was carried out in September 2014. This manufacturing plant visit included communications with First Solar staff at the site and covered CdTe module production and recycling processes, PV module quality and reliability test laboratory, in-house wastewater treatment facility, and debriefing on First Solar's EHS efforts. First Solar ensures authenticity and validity of all data provided for this report.

### 2.1.1. CdTe chemistry and toxicology

The compound CdTe has different qualities than the two elements, cadmium and tellurium, taken separately. Toxicity studies show that CdTe is less toxic than elemental Cd, which is a lung carcinogen, with long-term detrimental effects also on liver, kidney and bones due to calcium loss, but not as much is known about the compound CdTe [9,10,16,26]. CdTe has low acute inhalation, oral, and aquatic toxicity, and is negative in the Ames mutagenicity test[12]. Based on notification of these results to the European Chemicals Agency (ECHA), CdTe is no longer classified as harmful if ingested nor harmful in contact with skin, and the toxicity classification to aquatic life has been reduced [21]. Once properly and securely captured and encapsulated, CdTe used in manufacturing processes may be rendered harmless. Current CdTe modules pass the US EPA's Toxicity Characteristic Leaching Procedure (TCLP) test, designed to assess the potential for long-term leaching of products disposed in landfills [16]. Due to the strong ionicity of the CdTe and CdS compounds (72%) [40], the energy of any photon contained in sunlight is lower than the energy (> 5 eV) required to break the chemical bonds in CdTe or CdS. The strong bonding energies lead to an extremely high chemical and thermal stability, reducing the risk of degradation in performance or any liberation of Cd to a very low level, with no degradation intrinsic to the material to be expected [15].

Toxicological studies reviewed by Kaczmar on the toxicity of CdTe PV [9] were recently carried out in order to register CdTe PV under REACH in the European Union, and are briefly presented in Figure 15.

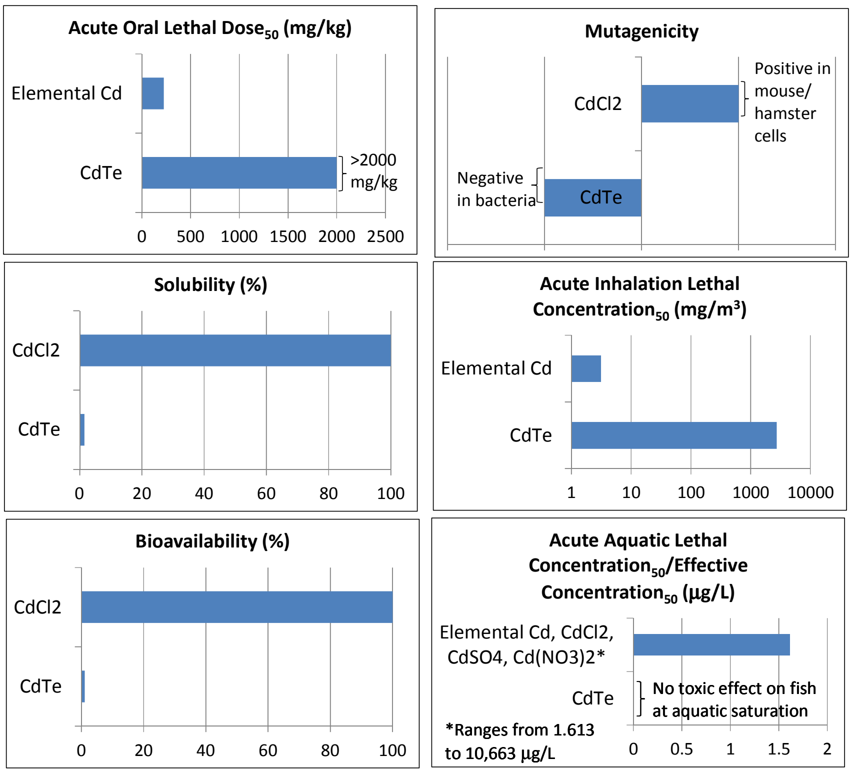


Figure 15: Toxicity, solubility and bioavailability of CdTe in comparison with other Cd compounds [9].

[12] The Ames test is a biological assay to assess the mutagenic potential of chemical compounds (http://www.princeton.edu/~achaney/tmve/wiki100k/docs/Ames_test.html).

In the processing of CdTe PV modules, First Solar uses CdTe and CdS, which are the active semiconductors that end up encapsulated between the two 3.2 mm thick glass panes, and also $CdCl_2$, which is sprayed on the CdTe layer to promote grain enlargement and improve photovoltaic conversion efficiency. CdTe and CdS are insoluble compounds, while $CdCl_2$ has a solubility of 1400 g/L [26]. After the grain enlargement process, however, $CdCl_2$ is washed off and is not a component of the finished PV module. Wastewater is treated on-site and tested to confirm compliance to permit limits before discharging (see Section 2.4).

### 2.1.2. Raw material sourcing and availability

Cadmium is a soft, bluish-white metallic element, one of the naturally occurring components in the earth's crust and waters, and present everywhere in our environment. It was first discovered in Germany in 1817 as a by-product of the Zn refining process. Its name is derived from the Latin word *cadmia* and the Greek word *kadmeia* that are ancient names for calamine or zinc oxide[13].

Tellurium is a brittle, mildly toxic, rare, silver-white metalloid, which is occasionally found in native form, as elemental crystals. Tellurium is far more common in the universe as a whole than it is on Earth. Its extreme rarity in the Earth's crust, comparable to that of Pt, is partly due to its high atomic number, but also due to its formation of a volatile hydride, which caused the element to be lost to space as a gas during the hot nebular formation of the planet. Tellurium was discovered in the Austro-Hungarian Empire in 1782 in a mineral containing Te and Au, and was named after the Latin word for "earth", *tellus*. AuTe minerals are the most notable natural Au compounds. However, they are not a commercially significant source of Te itself, which is normally extracted as a by-product of Cu and Pb production[14].

In this study, environmental, health and safety issues related to raw material sourcing in the production of CdTe PV solar modules are restricted to the active CdTe compound semiconductor itself, since from an EHS's perspective this is the most Cd-abundant material in this thin-film PV module production process, and also because CdS (active semiconductor material) and $CdCl_2$ (used for in-process grain enlargement, and then washed off) each contribute to only about 4% of the mass of CdTe used in module production. The active PV semiconductor device is comprised of both CdTe and CdS compounds, with thicknesses of up to 3 µm and 0.2 µm respectively. With the current First Solar CdTe PV module efficiencies of 15%, less than 54g of Cd, are used per

[13] http://www.cadmium.org
[14] http://www.mindat.org/min-3906.html

kWp (less than 5.8 g of Cd per individual 0.72 $m^2$ module, which is less than the Cd content of 2 x AA size rechargeable NiCd batteries [41].

CdTe is manufactured from pure Cd and Te, both of which are byproducts of smelting prime metals (e.g. Cu, Zn, Pb, and Au). Cadmium is generated as a byproduct of smelting Zn ores (~80%), Pb ores (~20%), and, to lesser degree, of Cu ores. Tellurium is a byproduct of Cu refining. Cadmium is used primarily in Ni–Cd batteries. Its previous uses in anticorrosive plating, pigments, and stabilizers were drastically curtailed. Cadmium is also used in the control rods of nuclear reactors. Tellurium is a rare metal used in manufacturing photosensitive materials and catalysts. Cadmium minerals are not found alone in commercial deposits. The major Cd-bearing mineral is sphalerite (ZnS), present in both Zn and Pb ores. Tellurium minerals are not found alone in commercial deposits. Tellurium is a rare metal that can be extracted as byproduct of processing Cu, Pb, Au, and Bi ores, and most of the tellurium is recovered from the slimes formed during the electrolytic refining of Cu [41]. CdTe is produced from Cd and Te powder via proprietary methods. CdTe is produced in small amounts for detectors and photovoltaics. Production is limited and the volumes produced are not published. Reportedly, 100% of the feedstock is used and there are no quantifiable emissions during CdTe formation. The electrolytic purification does not produce any emissions and all waste is recycled. The melting and atomization steps necessary to form the CdTe powder emit about 2% of the feedstock which are captured by High Efficiency Particulate Air HEPA filters [41].

The current and projected annual growth of the solar PV market, and the vision of solar becoming a relevant component of the electricity generation market will involve a few terawatts of PV to be installed worldwide before 2050. In this context, raw materials availability for CdTe PV module production might become an issue, and Te availability is the most critical aspect for this technology development at the gigawatt level. Current Te use in 3µm thick, 15% efficient CdTe solar cell devices is around 67 MT/GWp, with prospects of reducing this amount considerably by both efficiency increases and cell thickness reductions [35,42,43]. In 2010, CdTe PV module production accounted for about 26% of Te worldwide consumption [42], and as a by-product of Cu smelting, Te commercial availability is reportedly constrained to 16–24 GWp/year in 2020, 44–106 GWp/year in 2050, and 60–161 GWp/year in 2075 [43]. The projections shown in the literature have not counted on more Te from new BiTe ores, undersea ridges, or greater refining of non-Cu ores [35].

### 2.1.3. Manufacturing

As previously mentioned, First Solar owns CdTe PV module manufacturing capacity in the USA (PBG) and Malaysia (KLM) and complete, monolithically integrated PV modules are produced starting from glass and ending in a finished and ready-to-use glass-glass, unframed PV laminate. Figure 16 shows a simplified schematic representation of this process flow, in which semiconductor deposition, PV cell definition, and final assembly and testing of the finished PV module are all carried out at the same manufacturing facility.

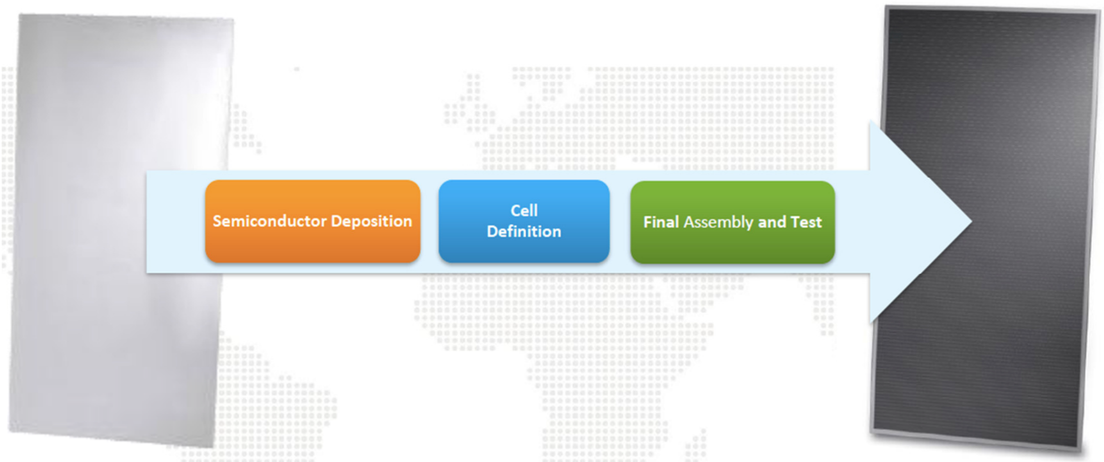


Figure 16: Conceptual and simplified flow of First Solar CdTe manufacturing process, from glass to finished PV module, in which all process steps are carried out at the same manufacturing plant.

For over two decades, originally as Solar Cells Inc., and since 1999 as First Solar Inc., the company has been engaged in the production of CdTe PV modules. During this period, much data has been accumulated on all facets of worker and environmental exposures to the Cd compounds used to manufacture this product. A large number of routine medical monitoring tests have been done on First Solar workers to track any biological responses to occupational Cd exposures. A similarly large number of industrial hygiene air samples have been collected to determine Cd exposure during specific manufacturing processes and maintenance procedures. Further, air emissions, emissions as industrial wastewater and solid wastes have been either measured or calculated using engineering estimates such as mass balance. The Cd management effort is complimented by a comprehensive safety management system. The heart of this system is a formal hazard recognition system designed to identify and proactively control workplace hazards [44].

First Solar devotes great care to the safety, industrial hygiene, and occupational health of employees, and carries out regular medical monitoring of staff involved in certain manufacturing activities (e.g. a comprehensive physical exam upon joining the company, and periodic blood and urine analysis). First Solar also has safety teams in place in each factory. First Solar has established an occupational, health and safety - OH&S management system (OHSAS 18001) to eliminate or minimize risk to employees and other parties who may be exposed to OH&S risks associated with the company's manufacturing activities, and has reduced the recordable incident rate - RIR at its factories from 2.6 in 2008 to 0.48 in 2014. Furthermore, in terms of Cd air contamination, the company has established a globally comparable air sampling strategy on a quarterly basis, and whenever there is a new plant or new equipment set up, potential exposure areas are barricaded and respirators are required within barricaded areas until qualification sampling is done and proven exposure controls are operating properly. Figure 17 shows the average Cd levels at the Malaysia KLM factory, which are well below the First Solar action limit of 1 µg/m$^3$. During certain maintenance activities Cd levels may exceed the action limit. During these activities, workers wear personal protective equipment such as HEPA respirators and impermeable coveralls.

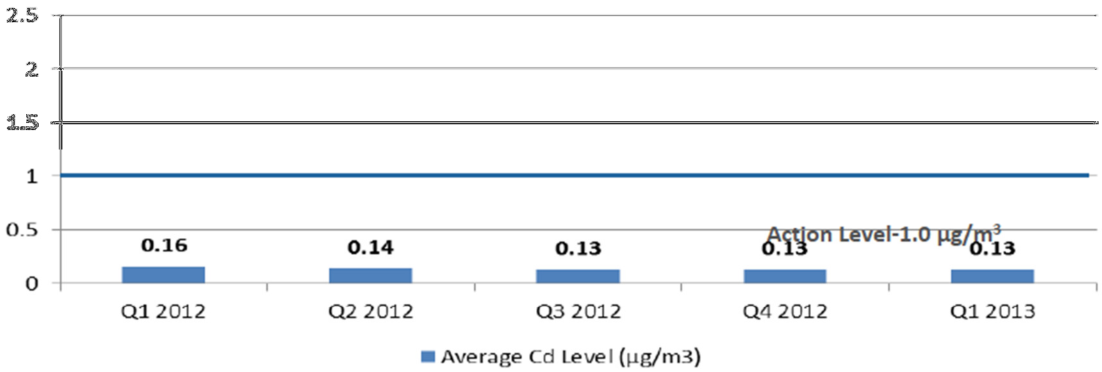


Figure 17: Cd levels routinely measured at the Malaysia KLM First Solar factory, which are well below the action limit of 1 µg/m$^3$.

Figure 18 shows sampling results of personal exposure to Cd at the various stages of manufacturing process at First Solar CdTe PV module production plants.

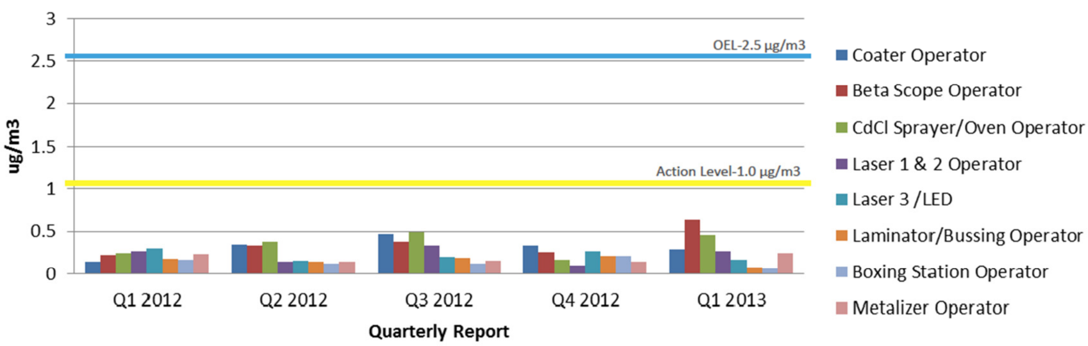


Figure 18: Personal exposure to Cd at First Solar manufacturing plants for the various stages of CdTe PV module production.

First Solar has accumulated several years of biomonitoring and industrial hygiene data, which are well below regulatory limits, and which validate the company's excellent control of Cd exposure. Figure 19 shows the biomonitoring results of First Solar's Perrysburg (top) and Malaysia (bottom) manufacturing site, where the mean blood and urine levels of employees are well below the Occupational Safety and Health Administration (OSHA) occupational health exposure limits.

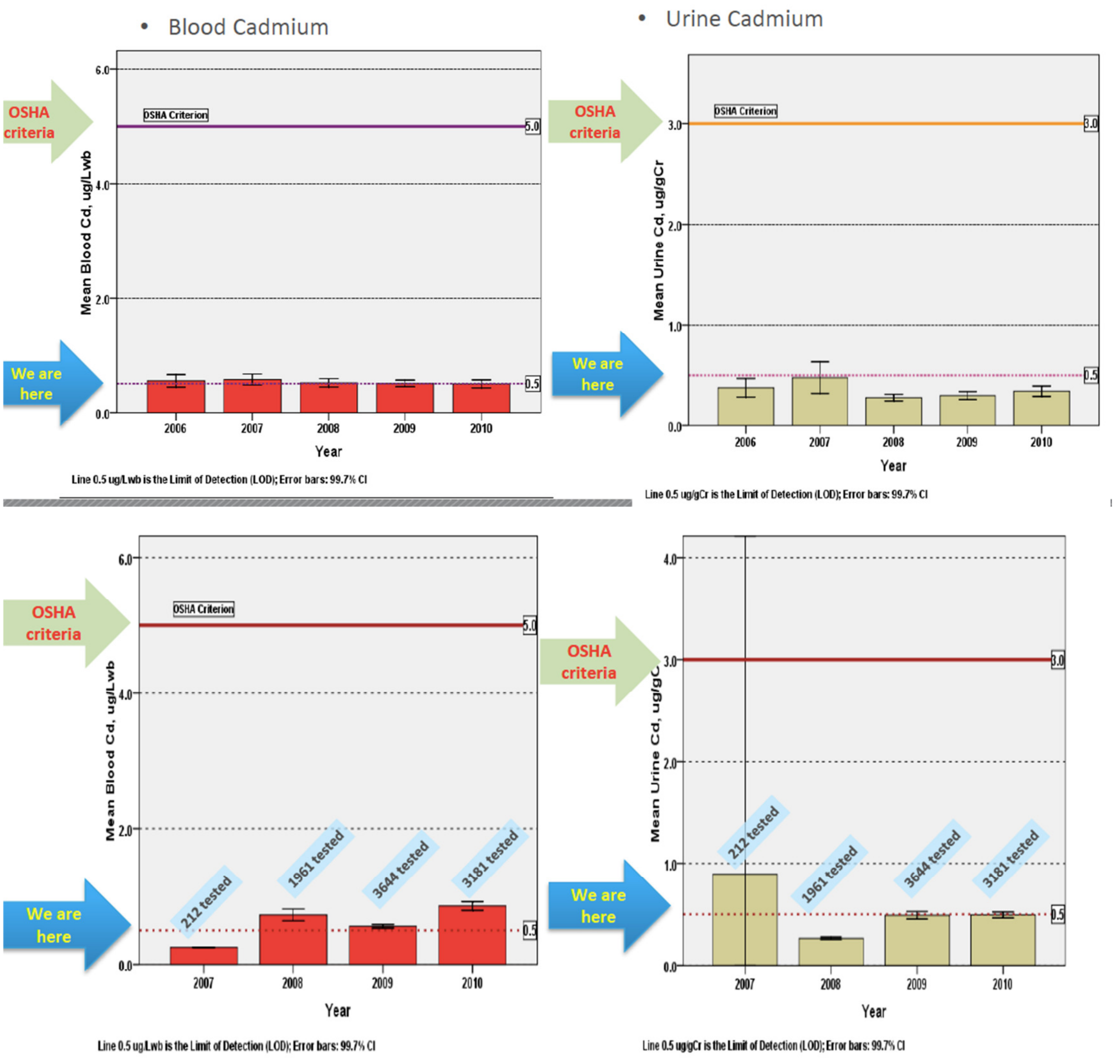


Figure 19: Biomonitoring results of First Solar's CdTe PV module manufacturing plant employees at the Perrysburg (top) and Malaysia (bottom) site.

Figure 20 shows a comparison between First Solar Malaysia (KLM) CdTe PV manufacturing plant employees pre-employment and employment annual Cd content in blood (top) and urine (bottom) for the year 2010 divided by smoking habit. A total of 3181 employees were tested (1253 pre-employment, and 2458 employed). There is no statistically significant difference between the Cd content of pre-employment and employment, but a distinct difference can be seen between the blood Cd content of smokers and non-smokers.

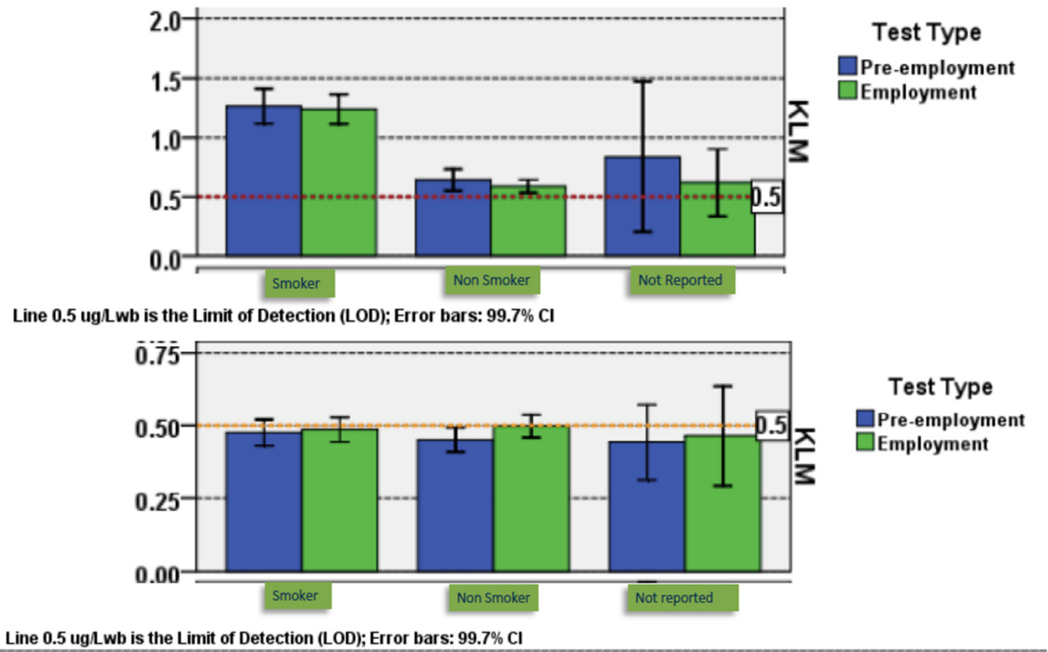


Figure 20: Evaluation of First Solar Malaysia (KLM) CdTe PV manufacturing plant employees' pre-employment and employment annual Cd content in blood (top) and urine (bottom) for the year 2010 divided by smoking habit. A total of 3181 employees were tested (1253 pre-employment, and 2458 employed).

First Solar has more recently started to consider the possibility of transferring part of the CdTe PV module manufacturing steps to other countries, in order to satisfy some local content requirements in new markets like Brazil. The concept of a so-called split line has been proposed by First Solar, and is schematically shown in Figure 21. It is expected that like in the current manufacturing plants, all new First Solar facilities will observe the same stringent EHS criteria.

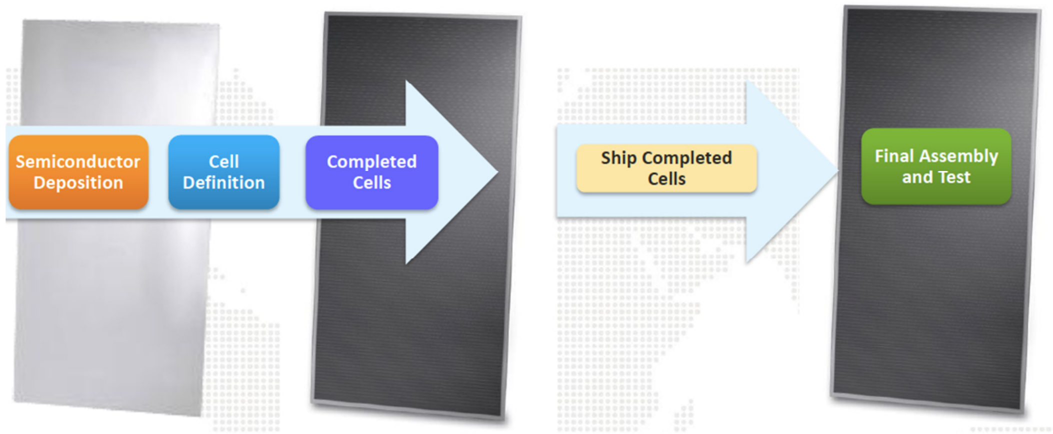


Figure 21: Conceptual and simplified flow of First Solar CdTe split line manufacturing process, from glass to finished PV module, in which some of the initial process steps are carried out at the base plant (PBG or KLM), and bundled single glass panes with completed cells are shipped elsewhere for final assembly and test at another manufacturing plant.

From an EHS standpoint, the manufacture of CdTe PV modules at First Solar is carried out in a controlled and responsible way. The processes from purchase of raw materials to manufacture of modules are all carried out in a closed workshop. Generated atmospheric pollutants generally enter the ventilation system of the workshop equipped with highly efficient HEPA (High Efficiency Particulate Air) filters. The efficiency of HEPA filters in collecting particulates of mean diameter of 0.3µm is 99.97%. Cleaning wastewater from all workshop sections flow to the in-house water treatment plant for centralized treatment. In this way, wastewater and air emissions generated at the site are effectively controlled. Wastewater and water use will be addressed in section 2.4.

### 2.1.4. Product use

It has been claimed that generating electricity with CdTe thin-film PV systems is an effective way of reducing the Cd content released into the environment (see section 2.2) [11,45]. This rationale is based on two main facts:

(i) Replacing coal-fired electricity generation with electricity generated with CdTe PV systems results in less Cd released to the environment, since coal contains Cd (140 g of Cd released for every GWh of electricity produced in the USA [46]), which is unavoidably released into the environment in coal-fired power plants. In CdTe PV systems, on the other hand, most of the Cd involved is trapped inside the glass-glass laminate. At the end of their useful life or when they are accidentally broken, CdTe PV modules can be disposed of in landfills, since they pass the US

Federal Toxicity Characteristic Leaching Procedure [15] (TCLP leaching criteria for non-hazardous waste [12]; and

(ii) Being a by-product of Zn mining and refining, and because Zn is produced in large quantities, substantial quantities of Cd are generated as an unavoidable by-product, no matter how much Cd is used in PV. This Cd can be either put to beneficial uses or discharged into the environment. When the market does not absorb the Cd generated by metal smelters and refiners, it is cemented and buried, stored for future use, or disposed of in landfills as waste, and arguably, encapsulating Cd as CdTe in PV modules presents a safer use than its current uses and is much preferred to disposing of it [11].

A solar PV module can suffer a breakage at any stage of its working life since transportation, installation, operation, maintenance operations and decommissioning all involve handling or exposure to other conditions that can result in surface damage (e.g. hailstorm events in certain areas). Measured module breakage rates are very low in First Solar's experience of over 2,000 MWp of CdTe PV plants operating in the USA, averaging 0.04%/year [47]. The CdTe compound will remain stable as a solid compound under normal operation conditions. In case of PV module breakage, chemical degradation is unlikely due to the low vapor pressure and low solubility of this compound and due to product design. In First Solar PV modules, CdTe is laminated between two sheets of glass and an industrial polymeric adhesive, which will prevent delamination if a module cracks. Even in a worst-case breakage scenario, potential impacts to soil, groundwater, and air from broken modules are within human health screening levels and background levels [47].

Fire is a common concern in the product use phase, and experimental analysis indicates that CdTe modules do not pose a significant risk during fires. Under the high temperatures of a building fire (800 to 1100˚C), module glass fuses together with Cd diffusing into glass, limiting release [48]. Potential impacts to air quality from CdTe PV fires have been found to be below human health screening levels [49].

### 2.1.5. Product end-of-life disposal and recycling

The most ideal way of disposing of CdTe PV modules at their end-of-life, as well as of broken/cracked modules in the field, or even for off-spec modules or modules damaged during the manufacturing process is recycling, and First

[15] TCLP is a U.S. hazardous waste characterization test. Under Brazilian law, waste containing Pb or Cd is listed as hazardous waste regardless of the volume of the chemical it contains (Brazilian Association of Technical Standards - ABNT by means of the normative NBR 10004:2004). Since Pb and/or Cd compounds are commonly used in commercial PV modules [9], these modules are likely to be characterized as hazardous waste at end-of-life if disposed of in Brazil. However, note that they will not be classified as waste or hazardous waste under Brazilian law to the extent that they are not finally disposed of in Brazil (e.g., transported outside of Brazil for recycling).

Solar has established a comprehensive recycling process in 2005, with recycling facilities operational in all manufacturing plants and an annual recycling capacity of around 26,000 MT. Figure 22 shows First Solar's PV module recycling process flow, consisting of a shredder; hammermill; reactor column, where PV module fragments are mixed with an acidic solution to separate the semiconductor materials from the solid glass and the encapsulant; and metal precipitation vessel. After precipitation and filter pressing, Cd- and Te-rich cakes are sent to third parties for Cd and Te refining, with up to 95% of the metals recovered. The shredded glass is sent to a third party, with 90% recovered, where it is used to produce new glass products. The encapsulant is disposed of according to local waste disposal standards or incinerated for energy recovery.

Releases to the environment could potentially occur after decommissioning only if such modules are disposed of in unlined landfills without leachate collection and treatment systems and assuming that the cadmium compounds leach out. However, cadmium telluride is encapsulated between two sheets of glass and is unlikely to leach to the environment under normal conditions [26,50].

Starting in 2014, the European Union regulatory framework on Waste Electrical and Electronic Equipment (EU WEEE) mandates recycling for all PV module technologies, with collection and recovery targets, as well as minimum treatment requirements. Recycling of PV modules is a growing and potentially profitable business, and with the inclusion of PV in the EU WEEE Directive, First Solar projects this business to yield around 17.5 billion Euros industry-wide by 2050, as recycling costs decline with volumes, as shown in Figure 23.

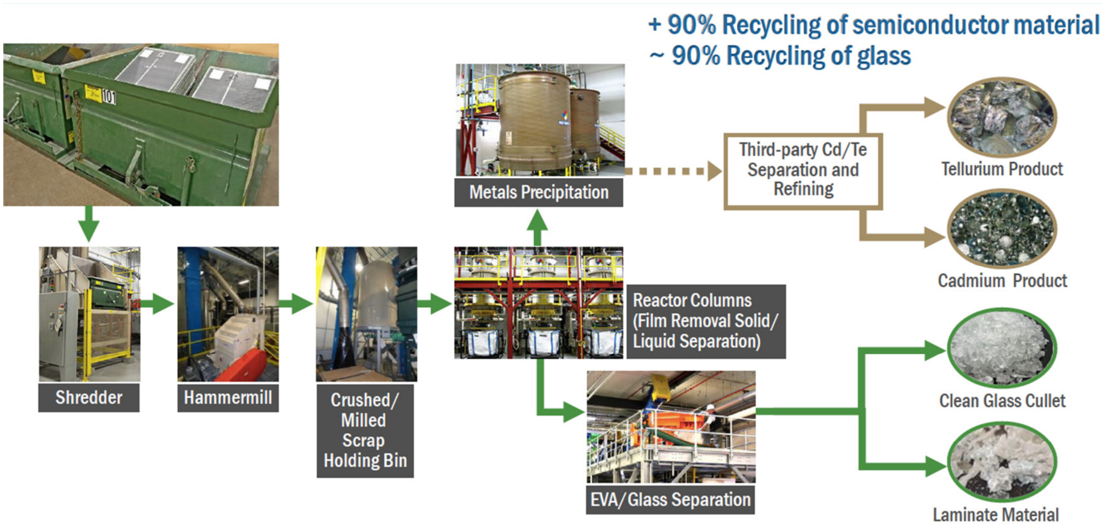


Figure 22: Process flow of First Solar's CdTe PV module recycling process. After metal precipitation carried out in-house, Cd and Te separation and refining are done by third parties.

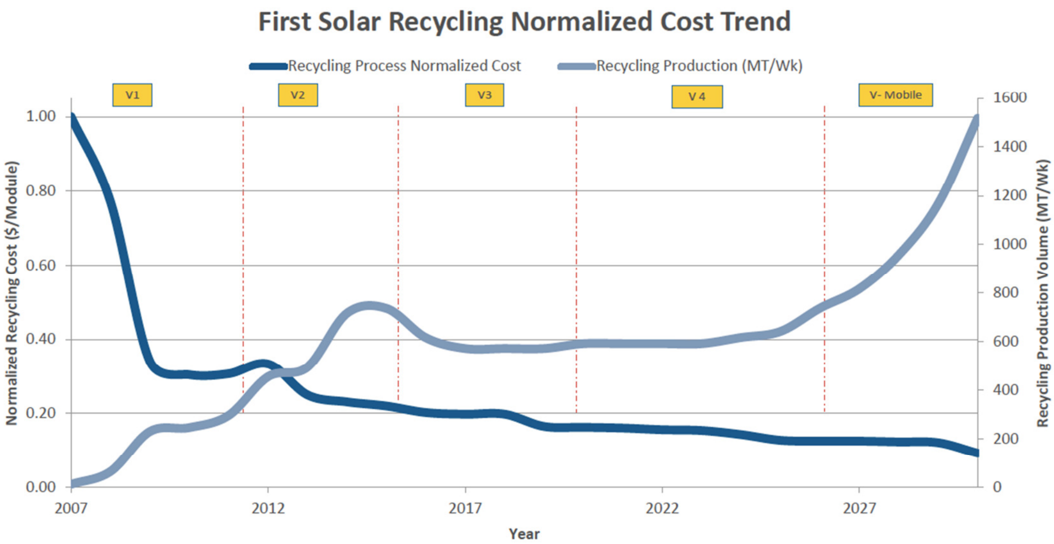


Figure 23: Evolution of the normalized recycling costs (US$/module) for First Solar CdTe PV module recycling process. Version V2 is currently in place, with V3 expected to come in line shortly.

## 2.2. Carbon footprint, Energy Pay Back Time (EPBT), and heavy metal emissions

Thin-film CdTe PV power plants will not increase heavy metal pollution to the environment during the normal installation and operation phases, but can bring Cd pollution to the atmosphere to some extent in the early phases including mining, ore grinding, roasting, smelting and refining. Relevant studies and First Solar data show that Cd pollution to the atmospheric environment can potentially be generated during solar PV module manufacturing, especially in the steps of thin-film production and crystal growth, and laser scribing. Cadmium-containing exhaust from the processes is generally disposed of in a compliant manner after dust collection, using 99.97% efficient High Efficiency Particulate Air (HEPA) filters, as shown in Figure 24. The remaining residual cadmium-containing pollutants in exhaust after dust collection are recirculated within the manufacturing facility with average factory-wide Cd concentrations in indoor air (<0.2 μg/m$^3$) that are well below occupational exposure limits (5 μg/m$^3$).

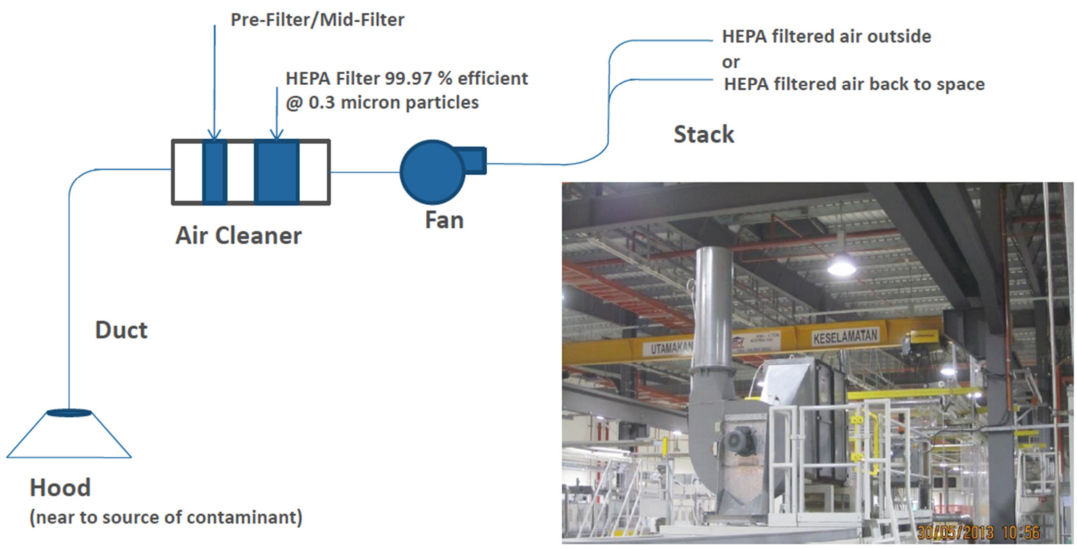


Figure 24: First Solar's CdTe PV module manufacturing plant Local Exhaust Ventilation (LEV) system. The photo shows the High Efficiency Particulate Air (HEPA) filter's exhaust air being recirculated back to the manufacturing floor space.

Han et al. [51] have reviewed the effects of environmental Cd on human health, and have concluded that it is important to (i) continue to conduct follow-up studies and analyze trends on health hazards, in order to evaluate Cd exposure and the severity of health damage related; (ii) collect and screen the information of population disease and death closely related to Cd exposure, and study the link and dose-response relationship between kidney damage and Cd exposure; (iii) establish human health hazard monitoring and early warning network of Cd exposure in the framework of environmental public health monitoring; (iv) implement prevention and intervention research on population health hazards of environmental Cd exposure to reduce contamination risks. Note that potential emissions from the mining and refining of Zn and Pb occur regardless of the use of their byproducts in PV [41].

In Figure 25, Fthenakis et al. [45] compared the lifecycle atmospheric Cd emissions of PV systems to other sources of electricity generation, showing the generating electricity with CdTe PV systems will release more than ten times less Cd into the environment, than producing electrical power on a coal-fired power plant.

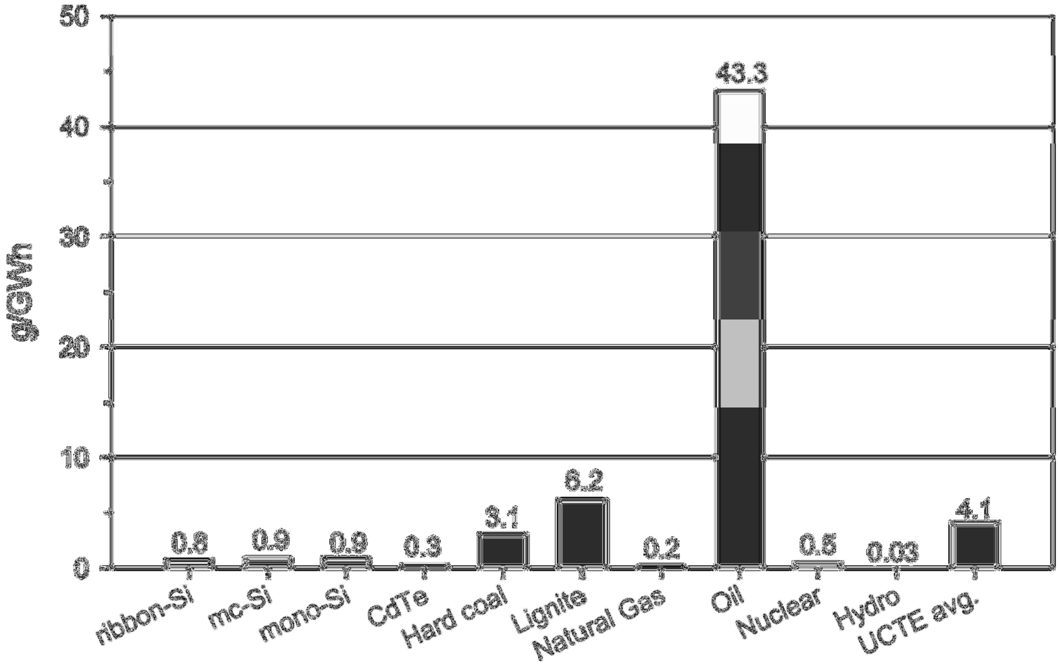


Figure 25: Lifecycle atmospheric Cd emissions for ground-mounted PV systems from electricity and fuel consumption for a Southern European average insolation of 1,700 kWh/m2/year, performance ratio of 0.8, and lifetime of 30 years [45].

The Energy Payback Times (EPBT) of the commercially-available solar PV technologies are shown in Figure 26. For all PV technologies, the energy involved in producing solar modules is paid back many times over the expected lifetime of a PV solar generator. Due to its low energy requirements, the manufacturing of CdTe PV modules presents the lowest EPBT in the photovoltaic industry.

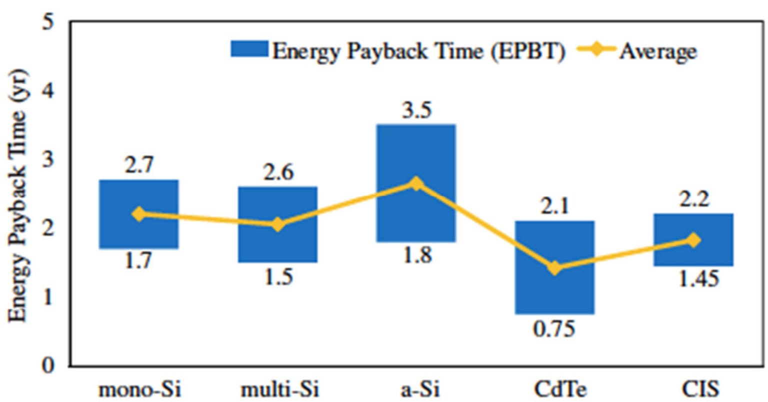


Figure 26: Energy Payback Times (in years) for commercially-available solar PV technologies [52].

A SimaPro LCA analysis of the carbon footprint was carried out by First Solar for solar farms using 15% First Solar CdTe PV modules operating in Brazil[16] for different combinations of optimum annual electricity yield (2,000 and 2,300 kWh/kWp/year), 80% Performance Ratio, annual output degradation (0.5 and 0.7 %/year), and power plant lifetime (25 and 30 years). $CO_2$ footprint values for First Solar's CdTe PV systems ranged from 11.9 to 16.6 g $CO_2$-eq/kWh for PV modules produced using the USA energy mix, and from 9.6 to 13.4 g $CO_2$-eq/kWh for PV modules produced using the Brazilian energy mix. Energy payback times for First Solar CdTe PV plants operating in Brazil varied from 0.82 to 0.94 years at the sunniest sites, to 1.22 years under the worst possible solar irradiation conditions in the country. The $CO_2$ footprint values for crystalline silicon PV, on the other hand, are considerably higher, ranging from 30 to 60 g $CO_2$-eq/kWh for multi- and monocrystalline silicon respectively, and the EPBT range from 1.82 to 3.07 years respectively.

## 2.3. Land use and biodiversity

Renewable energy sources are typically dispersed and difficult to collect, thus requiring substantial land resources in comparison to conventional energy sources. Fthenakis and Kim [53] have presented the normalized land requirements during the life cycles of conventional and renewable energy options, covering coal, natural gas, nuclear, hydroelectric, PV, wind, and biomass. They have compared the land transformation and occupation matrices within a lifecycle framework across those fuel cycles. Although the estimates vary with regional and technological conditions, the PV cycle requires the least amount of land among renewable-energy options, while the biomass cycle requires the largest amount. Moreover, they have determined that, in most cases, ground-mount PV systems in areas of high insolation transform less land than the coal-fuel cycle coupled with surface mining. In terms of land occupation, the biomass fuel cycle requires the greatest amount, followed by the nuclear fuel cycle.

Solar PV is an area-intensive energy generation technology, and at 15% conversion efficiency PV modules installed side by side on a horizontal surface will lead to a nominal power of 150 W/m$^2$ (6,667 m$^2$/MWp). However, land is required in addition to that accommodating the PV module array, for access, maintenance and also to avoid shading. At the low-latitude sites in Brazil where most of the PV solar farms will be installed, PV modules will be mounted on fixed metal racks typically tilted at 10$^o$ facing true North (or on single-axis tracking structures). For fixed PV arrays, module spacing and distance between module rows (a typical pitch is 2.5 m) will lead to area requirements of about 14,000 m$^2$/MWp.

[16] Assuming the Brazilian current electricity generation mix and a grid efficiency of 64%.

The largest potential impact of utility-scale PV solar plants to wildlife and habitat is due to land occupation by the solar power plant itself. If the solar power plant is enclosed by a fence, hiding spots, preying strategy, and food availability will all be affected. Power plants can also prevent vegetation growth, and a significant alteration to the vegetation might occur. The PV arrays themselves will cast shadows and might change the microclimate, causing effects on vegetation that have not been previously studied. The installation of a PV power plant might involve suppression of vegetation in the development area, with withdrawal of soil vegetative coverage favoring erosive processes. In most of the regions where solar PV plants are likely to be installed in Brazil, the land is not particularly adequate for agricultural activities, and it is not envisaged that PV power plants will compete with agricultural or livestock production, or lead to the removal of forests in this 8.5 million square km country. However, the impact to wildlife will be tightly correlated to the biodiversity of the land on which the solar power plant is built. Sunlight and water availability can significantly alter the biodiversity in any of these biomes. Consequently, a customized study of the wildlife and ecosystem surrounding each power plant is recommended as a best practice. In addition to potential impacts on biodiversity, solar projects can have potential benefits for biodiversity due to their static use of land [26]. Although construction projects always involve disturbance of existing flora and fauna, with solar parks there is a chance to improve the quality of habitats for various plant and animal species and even to create new habitats [54]. Table 2 summarizes ecological impacts of solar power plants displacing power generated by the traditional U.S. technologies.

Table 2: Impacts to human health and well-being (top) and wildlife and habitat (bottom) of solar electricity generation relative to traditional USA power generation [55].

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

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

## 2.4. Water use, wastewater treatment and disposal

Water use in the electricity generation with PV in general, and with thin-film CdTe PV in particular was analyzed by Fthenakis et al. and Sinha et al. [3,4] respectively, and they have found that in any case, PV-generated electricity involves less water consumption and water withdrawal than any of the conventional, and most of the renewable energy generation options except for wind.

The industrial preparation and processing of CdTe PV modules involves the cadmium compounds CdTe, CdS and $CdCl_2$. First solar manufacturing wastewater contains up to 30 ppm of Cd, and standard metal precipitation technology removes Cd to approximately 100 ppb. First Solar adds filtration and ion exchange polishing technologies to reduce Cd levels to less than 20 ppb. Wastewater systems operate in a batch discharge mode. After treatment, water is collected in holding tanks, which are sampled and tested to confirm compliance to permit limits before discharging, and if not compliant, water is sent for re-treatment internally. First Solar factories are equipped with state-of-the-art analytical capability for in-house water testing of Cd. Figure 27 shows a process flow diagram of the wastewater treatment at First Solar manufacturing plants, and Figure 28 shows some of the equipment used at First Solar's dedicated wastewater treatment plant.

From 2009 to 2013, First Solar has reduced the amount of water necessary for manufacturing CdTe PV modules from 1.87 to 1.46 liters per Wp. Note that water withdrawal for CdTe PV manufacturing is lower than c-Si PV manufacturing due to a less energy and material intensive manufacturing process [3].

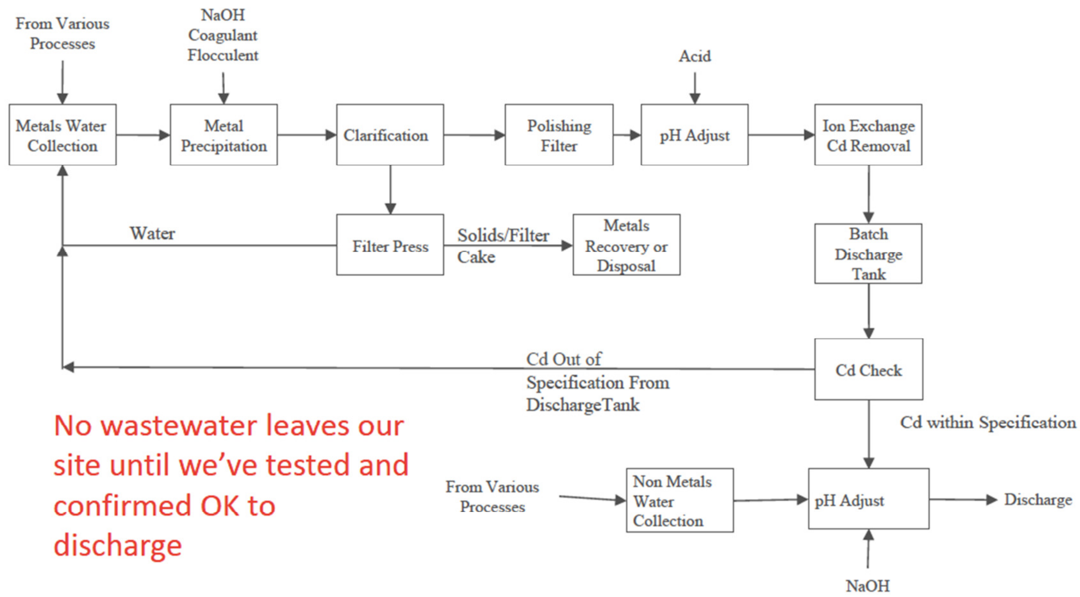


Figure 27: Process flow diagram of the wastewater treatment at First Solar manufacturing plants.


Figure 28: Equipment used at First Solar's dedicated wastewater treatment plant.

After treatment, First Solar Cd mass balance indicates that less than 0.02% of the total incoming Cd is released into water, and is well below regulatory final discharge limits.

# 3. Performance aspects of PV in warm climates

Less than 10% of PV systems worldwide are located in tropical regions [56]. With favorable irradiance conditions and the cost reductions experienced by PV technologies in recent years, installations in these areas of the world are expected to grow substantially in the near future. Irradiance, operating PV cell temperature and the spectral content of sunlight are the three most relevant parameters affecting the performance of PV devices in the field, and they can vary considerably from site to site, depending on whether a solar PV plant operates in the more traditional, temperate climate, PV markets, or in hot and sunny sites. Even at sunny sites with similar solar irradiation resource availability, wind speed influences PV module operating temperatures considerably and must be taken into account. Additionally, soiling issues are a matter of much greater concern in warm and sunny climates, and as different arid and desert sunny sites around the globe start to deploy PV plants in larger volumes, soiling needs to be addressed with greater care.

## 3.1. Performance of CdTe PV in hot and humid climates

Due to intrinsic material characteristics, thin-film CdTe and a-Si have been reported to present superior output performance in the field in sunny and warm climates [57,58]. With the considerable advances that CdTe PV has obtained in terms of both efficiency increases and manufacturing cost reductions, full-size commercial CdTe PV modules are currently double the efficiency of their a-Si counterparts. As operating temperatures in the field rise, all solar PV devices suffer performance losses, and among the commercially-available PV technologies, CdTe and a-Si are the ones with the lowest negative temperature coefficient of power, namely -0.25 to -0.34 %/$^{o}$C for CdTe [59] and -0.10 to -0.20 %/$^{o}$C for a-Si [36]. The more traditional crystalline silicon PV technologies have temperature coefficients ranging from -0.45 to -0.50 %/$^{o}$C, and might therefore suffer double the performance losses of their thin-film counterparts. Figure 29 shows the distribution of ambient and back-of-module surface temperatures measured in a First Solar PV array in the USA desert Southwest area.

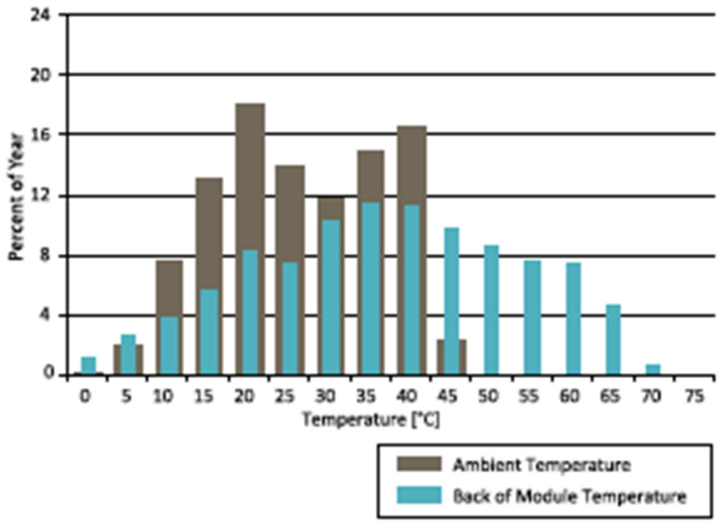


Figure 29: Distribution of ambient and back-of-module surface temperatures measured in a First Solar PV array in the USA desert Southwest area [58].

Figure 30 shows the distribution of the fraction of power production as a function of back-of-module temperatures for a First Solar PV power plant operating in the USA desert Southwest area.

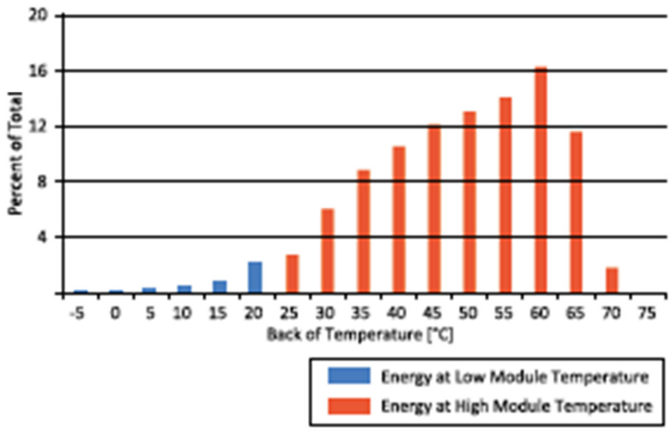


Figure 30: Distribution of the fraction of power production as a function of back-of-module temperatures for a First Solar PV power plant operating in the USA desert Southwest area [58].

These figures show that there is a considerable portion of time and energy produced by a PV system in a warm climate that is generated at temperature conditions far above the Standard Test Conditions of 25°C PV cell temperature. While these conditions indicate a superior performance expectation of First Solar's CdTe PV devices from a semiconductor characteristics point of view, they are also challenging from the standpoint of other PV device failure mechanisms, and First Solar is expecting to have slightly higher warranty failure rates in high-temperature climates. First Solar recommends a -0.7%/year long-term degradation rate in the modeling of long-term performance of CdTe systems in hot climates, instead of the -0.5%/year recommended in more temperate climates [58]. Going forward, First Solar has recently introduced a new cell structure with improved back-contact design that better manages the fundamental power output degradation mechanism inherent to CdTe PV devices. The improvement over plant lifetimes in long-term degradation rate afforded by the new back contact enables First Solar's long-term degradation guidance to be improved to –0.5% per annum for all climates [59].

## 3.2. Soiling

As PV develops into the multi-gigawatt range, the largest, utility-scale PV power plants are being installed in areas of the globe where soiling issues need to be taken into account. Soiling has been a matter of investigation at many sites worldwide, from Saudi Arabia [60] to the USA Southwest [61,62], and in the sunny Malaga region in Spain [63] and Kuwait [64], among many others.

The soiling of PV modules is an important issue regarding PV module power output. Anti-soiling coatings, which aim to reduce soiling losses, are a very interesting and promising topic [60]. Depending on the environmental conditions, the different surface structures and anti-reflection coatings which are applied on the glass in order to increase the annual gain of a PV module may turn non effective and glass transmittance may decrease below the level of unstructured or uncoated glass. Former investigations revealed enormous efficiency losses due to heavy soiling, up to -80% within a period of 6 months [60].

In the Brazilian emerging PV market, utility-scale PV power plants will also be deployed at sites where soiling will be an issue. Figures 31 and 32 show some examples of testing sites in the Brazilian Northeast where different PV module technologies are being deployed side by side to investigate soiling effects on PV system performance among other effects of operating solar farms in sunny and warm areas in Brazil.

Figure 31: Example of heavy, uniform soiling conditions at a PV test site in the Brazilian Southeast.

Many of the sunny sites in Brazil where PV power plants will be installed are also very windy sites, and PV power plants will often operate side by side with wind parks, as shown in Figure 32. An advantage of the windy sites is that PV modules will operate at lower temperatures and consequently suffer lower output losses due to temperature effects. However, wind also increases soiling, and promotes non-uniform distribution of soiling as shown in Figure 32, which might lead to adverse effects on performance that are often PV module design-, PV system electrical design- and layout-specific.

Figure 32: Examples of heavy, non-uniform soiling conditions at a PV test site in the Brazilian Southeast; non-uniformities in soiling patterns are mainly caused by strong wind conditions.

## 3.3. Reliability testing

In order for solar power to be able to compete with conventional electricity generation technologies, PV power plants have to reliably deliver power for 25-30 years, operating in the harsh environmental conditions in the field. PV module manufacturers offer product warranties of up to 10 years, and performance warranties are typically 25 years for 80% of the initial or nominal power. First solar maintains a reliability laboratory with first class ISO 17025 calibrated, automated equipment and data collection, and an extensive personnel training program. Table 3 shows some figures on the extensive reliability testing program currently in place at First Solar's manufacturing facilities in the USA and Malaysia, as well as at test sites around the world.

Table 3: Figures on First Solar's extensive testing of CdTe solar PV modules in the Perrysburg-OH manufacturing plant and elsewhere.

| | Perrysburg | Global |
|---|---|---|
| Modules Tested Per Year | 40,000 Modules | 80,800 Modules |
| Modules Currently In Test | Over 1300 Modules | Over 4000 Modules |
| MW Tested Per Year | Over 3.5 MW | Over 4.4 MW |
| Reliability Lab Space | 28,800 SqFt | 64,300 SqFt |

Recent advances in CdTe research and development have improved the long-term power-output degradation and extended reliability test performance of First Solar's thin-film CdTe PV modules. First Solar has recently introduced a new cell structure with improved back-contact design that better manages the fundamental power output degradation mechanism inherent to CdTe PV devices [59]. First Solar's proprietary 'Black' series module construction significantly enhances the long-term durability and extended test performance of the modules. The accelerated lab testing methods, field testing and associated analyses are carried in many sites around the globe. The advances in the solar cell performance, coupled with upgraded module materials, further substantiate the long-term power-generating capability of First Solar's CdTe PV modules in harsh operating conditions [59].

First Solar's reliability laboratory carries out activities in support of developments in high volume manufacturing (process monitoring), new product and process development, product reliability (new product and process qualification and certification, assistance in the preparation of technical notes and product data sheets, warranty (accrual predictions and field performance validation). The reliability lab capabilities include environmental (56 chambers) and light-soaking (143 chambers) facilities for accelerated testing of products and packages; static and dynamic loads to simulate wind, snow and ice loads at varying temperatures and rates; reverse current overload (RCOL), for determining the risk of fire under reverse current fault conditions; UV chamber, to accelerate UV exposure in order to evaluate materials and adhesive bonds susceptible to UV degradation; hail impact test, to verify PV module capability of withstanding the impact of hail; module breakage test, a safety test designed to provide confidence that cutting or piercing injuries are minimized when a PV module is broken; hot spot test, to determine the ability of a PV module to withstand heating effects caused by soiling or shading; impulse voltage test, to verify the capability of the solid insulation of the PV module to withstand over-voltages caused by a lightning strike; power characterization of PV modules at Standard Test Conditions and at varying temperature and irradiance conditions using a Class AAA solar simulator; wet & dry HiPot measurement facility, to evaluate the insulation of the PV module under wet operating conditions and verify that moisture does not enter the active parts; module thickness measurements, to characterize PV module thickness and relative shape; automated visual inspection, to detect any visual defects in the PV module; and near-IR measurements, to detect any defects in the module which are visible as a result of electroluminescence.

In addition to the above range of module reliability testing, First Solar has recently undertaken long-term parallel testing in recognition of the need to extend test durations to better differentiate PV modules in long-term field performance [59]. For example, in the Thresher Test, the conventional IEC test environmental stress exposure durations are multiplied by a factor of two to four in order to identify those modules with truly differentiated long-term reliability and performance. First Solar is the first thin-film PV manufacturer to pass the extended accelerated life cycle testing protocols of the Thresher Test and Long Term Sequential Test [65]. First Solar is also the first PV company to obtain the new VDE Quality Tested (QT) Certification for PV power plants (module and balance of system) [66].

## 3.4. Grid integration

The integration of utility-scale solar PV generators in the electricity grids worldwide represents at the same time an opportunity and a challenge. PV power plants that support grid stability and reliability are becoming available as PV generation grows to the point of making a significant contribution to the grid. Dynamic voltage regulation, active power management, ramp-rate control, frequency droop control and fault-ride-through capability are all aspects related to grid-friendly PV plants that are operational today [67]. Figure 33 shows a schematic diagram with an example of a plant control system and interfaces to other components, and Figure 34 shows an example of a large, utility-scale 290 MWp CdTe PV module power plant with grid-friendly plant control. The plant controller provides the following plant-level control functions:

• Dynamic voltage and/or power factor regulation of the solar plant at the point of interconnection (POI);
• Real power output curtailment of the solar plant when required, so that it does not exceed an operator-specified limit;
• Ramp-rate controls to ensure that the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible;
• Frequency control to lower plant output in case of over-frequency situation or increase plant output (if possible) in case of under-frequency; and
• Start-up and shut-down control.

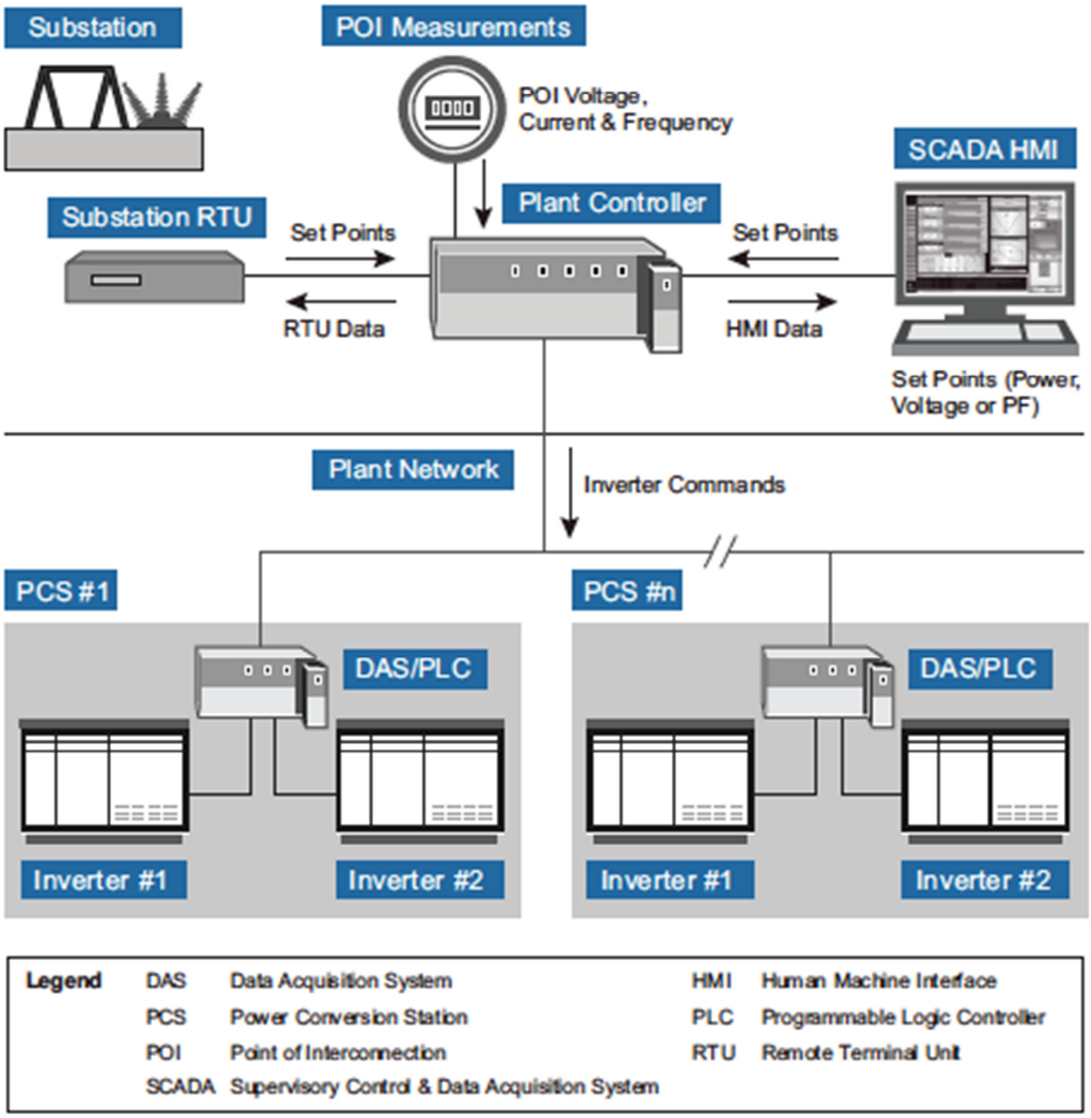


Figure 33: Example of a plant control system and interfaces to other components [67].

First Solar owns and operates a Solar Operations Center in Tempe-AZ, USA (Figure 35), from which it currently monitors the performance of over 2,000 MWp of CdTe PV power plants in the USA.

Figure 34: First Solar's Yuma County-Arizona, 290 MWp CdTe PV power plant with grid-friendly plant control [67].

Figure 35: First Solar Operations Center in Tempe, Arizona, from where the company controls over 2,000 MWp of solar power plants operating in the USA [67].

## 3.5. Field performance data

Utility-scale PV power plants are rapidly growing in size and number, but very little is reported publicly on the specific performance of large solar power plants and how their actual, measured output compares with common modeling tools that are used to price and sell the assets [68]. Typically, a PV power plant is sold largely on the basis of a calculation of the long-term average annual energy yield. One common strategy for generating long-term predictions uses satellite meteorological data and estimated loss assumptions along with a common simulation tool, such as PVSyst[17], to model the behavior of the power plant over a "typical" year. Panchula et al. [68] have compared the measured output performance of the Sarnia 20 $MWp_{AC}$ power plant in Ontario, Canada after one year of continuous operation, to both the long-term energy prediction and the expected energy for the operating year 2010. Based on the first year's data, the power plant was shown to be operating 2.1% above the long-term prediction, well within the expected error-bars of the measurements.

In a long-term experiment with First Solar (formerly Solar Cells Inc.) 1995-vintage thin-film CdTe PV modules, after almost two decades of monitoring, the US National Renewable Energy Laboratory - NREL confirms the excellent reliability of First Solar's module technology, with no module failures in system operation [58]. Figure 36 shows the evolution of the DC power of the CdTe modules over 17 years (1995-2012), with a -0.53%/year degradation rate in the temperate climate of Colorado. USA.

The predicted energy ratio (PER) is the lifetime ratio of actual energy produced to the energy predicted. Figure 37 shows the average PER, by commissioning year, for 270MW (including >130MW of hot-climate deployments) of installed PV systems using First Solar CdTe modules. The PER substantiates First Solar's field performance record and validates First Solar's accuracy in predicting field performance. Current degradation guidance of –0.5%/year in temperate climates and –0.7%/year in high-temperature climates is First Solar's recommendation for long-term performance PV systems modeling [58]. As previously mentioned, First Solar's new cell structure with improved back-contact design enables First Solar's long-term degradation guidance to be improved to –0.5% per annum for all climates [59].

[17] http://www.pvsyst.com/en/

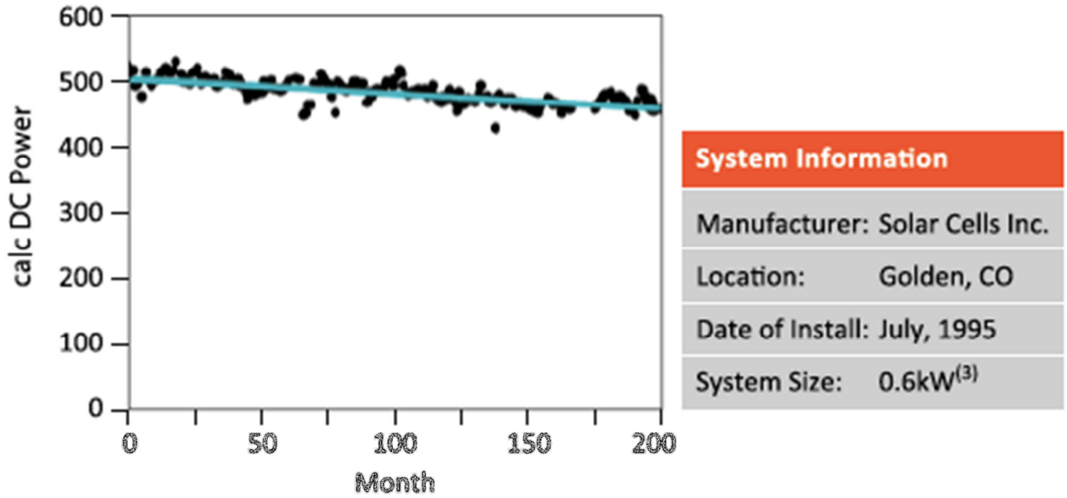


Figure 36: Long-term performance assessment of First Solar (formerly Solar Cells Inc.) CdTe PV modules carried out by the National Renewable Energy Laboratory – NREL, from 1995 to 2012. Annual output power degradation rate is 0.53%/year [58].

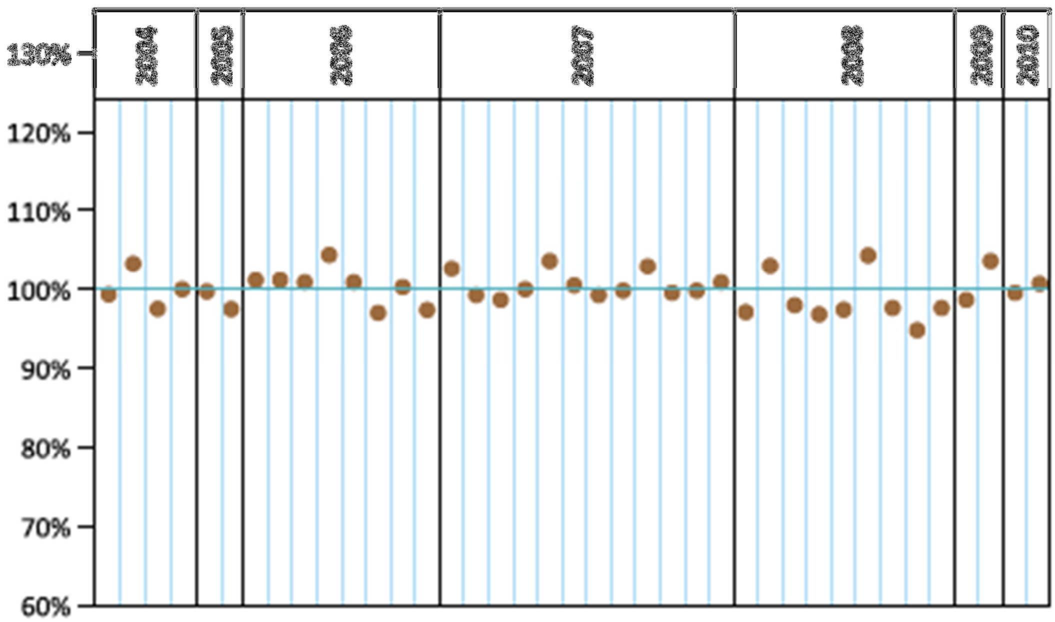


Figure 37: Average Predicted Energy Ratio – PER, by commissioning year, for 270MW of thin-film CdTe PV systems using First Solar modules: >270MW monitored installations base, including >130MW of hot-climate deployments [58].

# References and further reading

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