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

Project title	**Assessment of performance, environmental, health, and safety aspects of First Solar's CdTe PV technology**
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The authors are solely responsible for their contributions in this work.

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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.

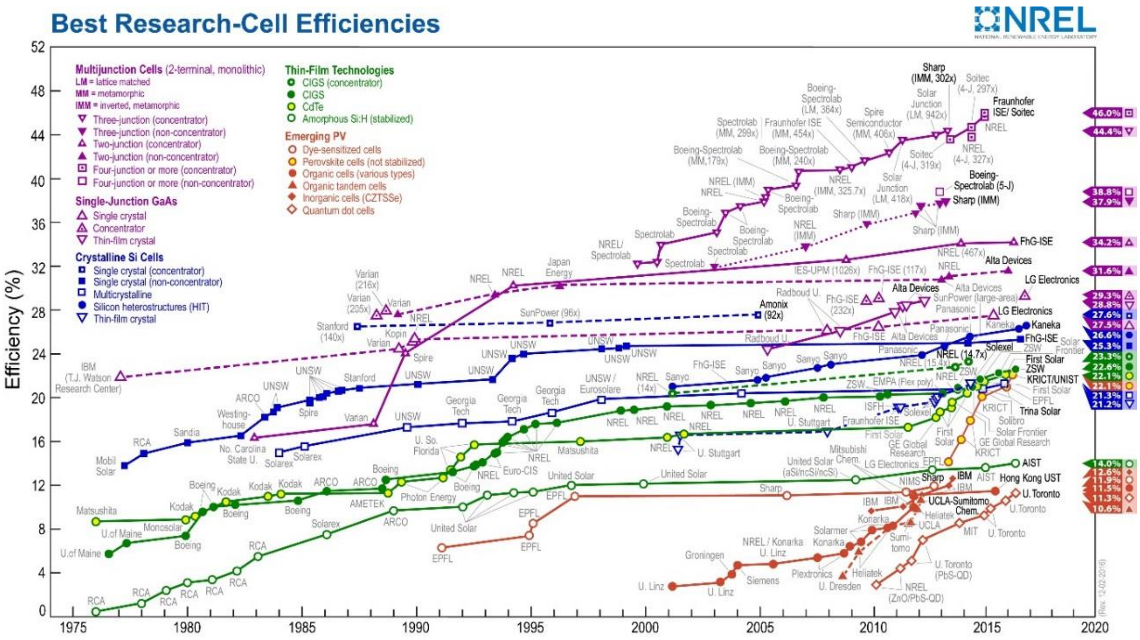


Figure 1 Record efficiencies of PV Solar cells (from NREL as of 17th December 2016).

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].

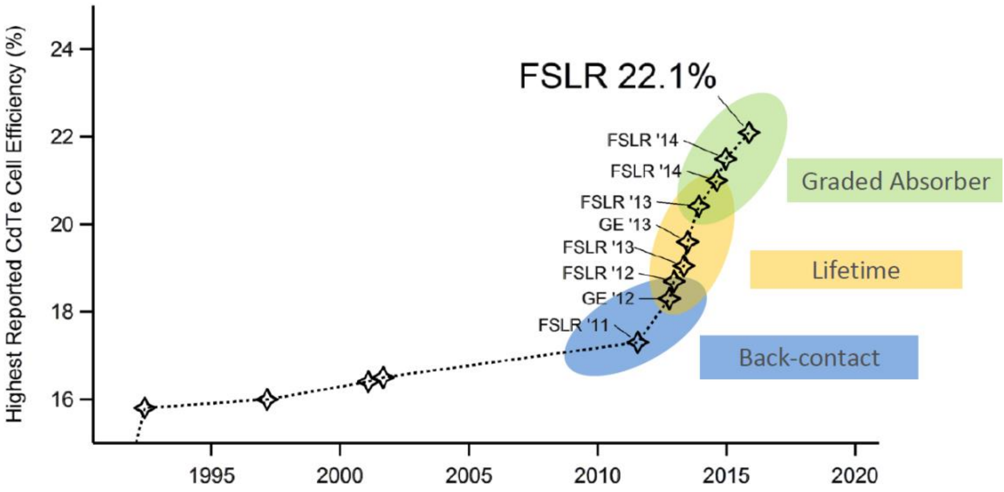


Figure 2 CdTe record cell efficiency evolution.

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.

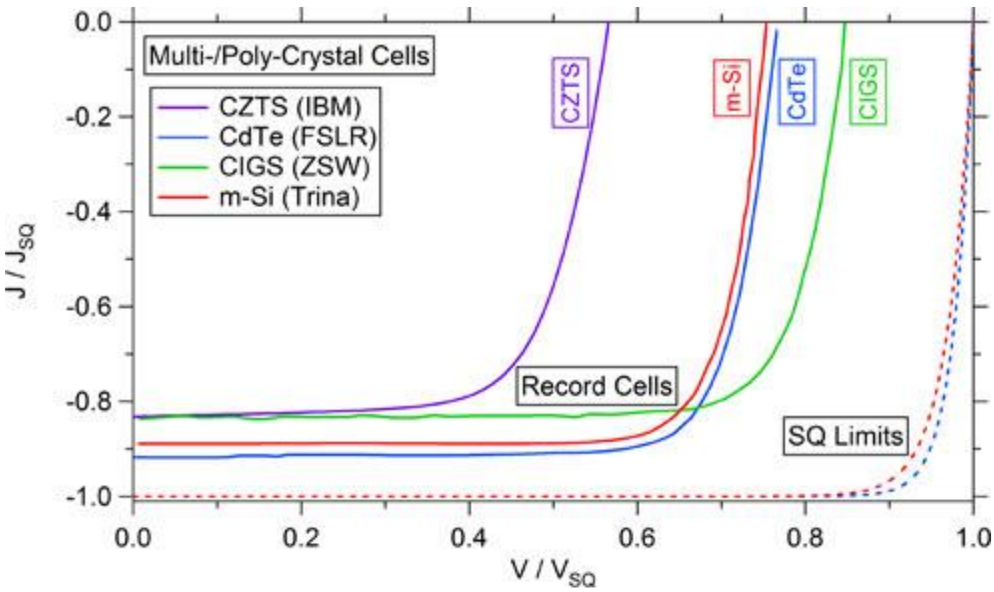


Figure 3 Comparison of the I-V curves of record cell technologies (CIGS, CdTe and m-Si) with the ideal Shockley Queisser limit[9].

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.

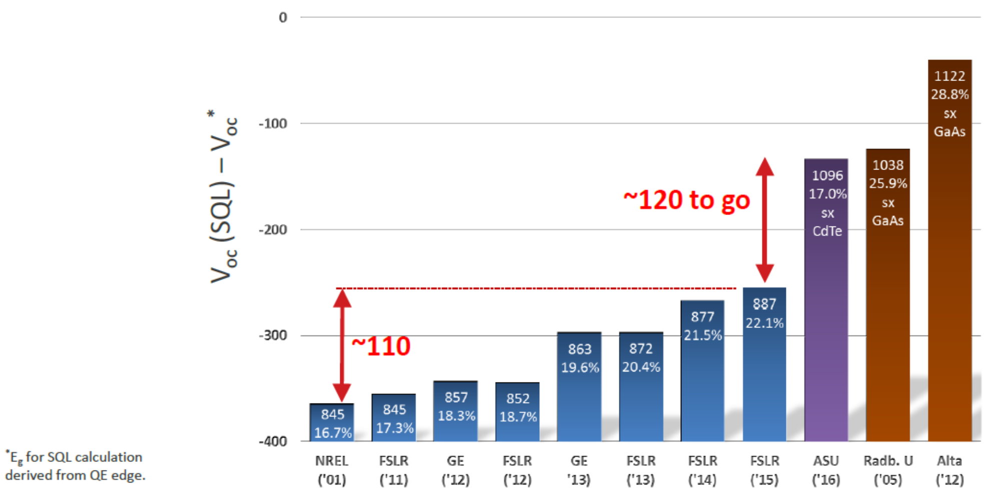


Figure 4 Roadmap for open circuit voltage improvement in CdTe solar cells, expressed in mV and compared to reference devices, single crystal CdTe and GaAs devices. The Y value corresponds to the difference between the calculated theoretical open circuit voltage from the band gap value and that of the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

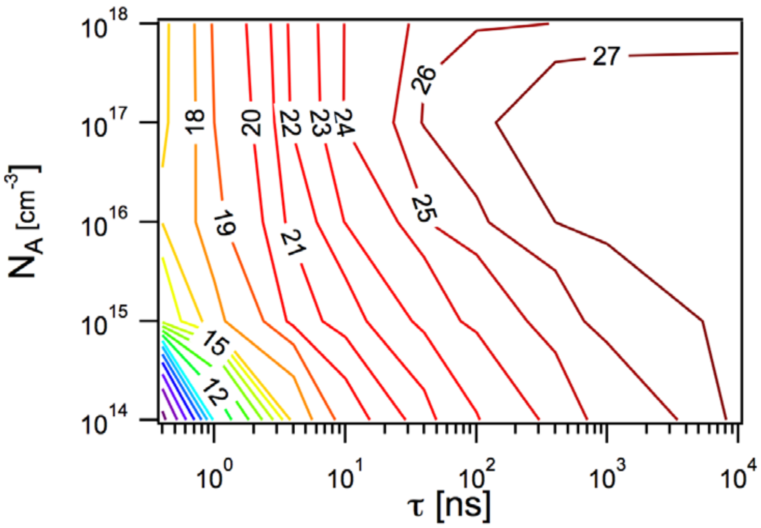


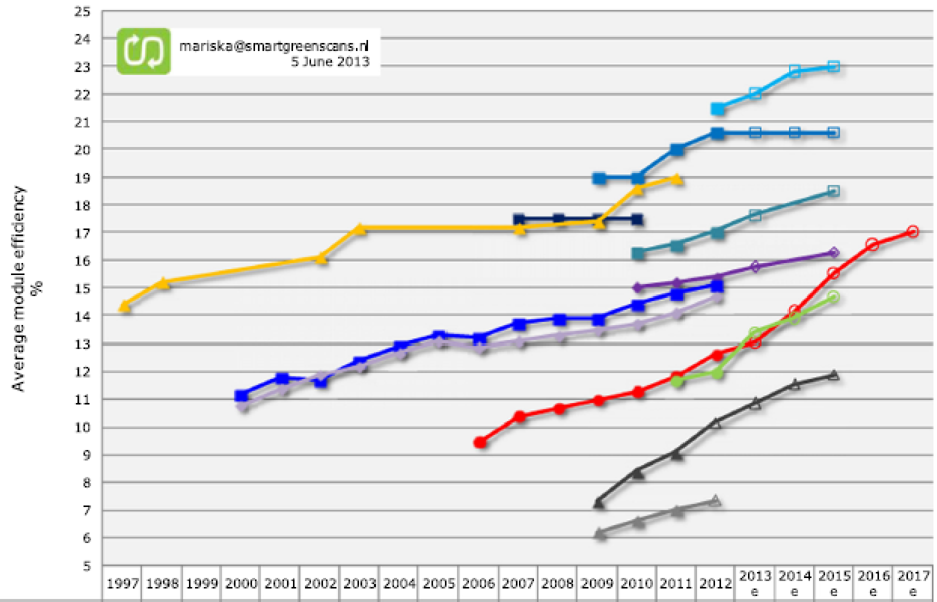
Figure 5 Simulated contour plots of conversion efficiencies of CdTe solar cells versus bulk life time and acceptor doping level[7].

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.

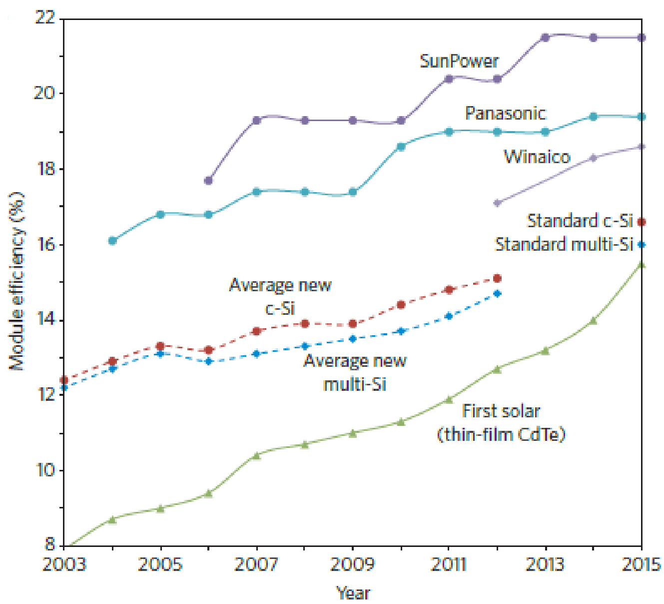


Figure 7 Evolution of module energy conversion efficiencies as a function of the technologies.

[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.

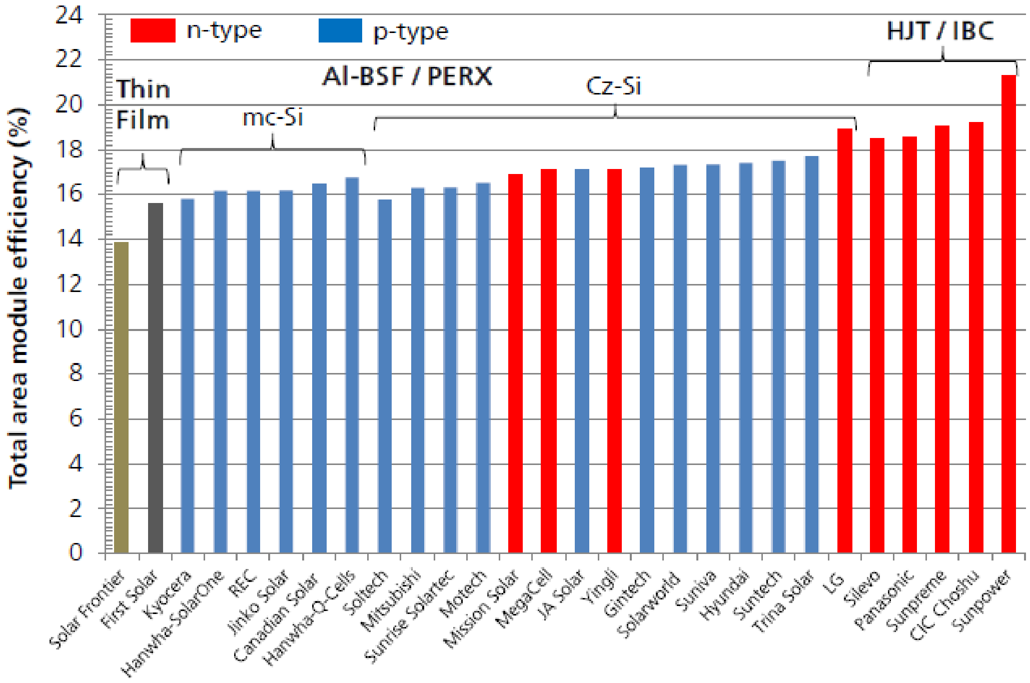


Figure 8 Current efficiencies (as of November 2015) of selected commercial PV modules companies sorted by bulk material cell concept and efficiencies.

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

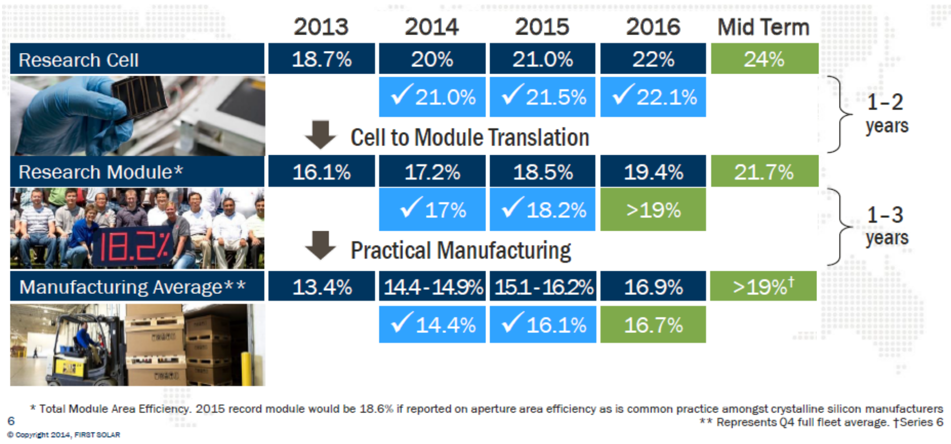


Figure 9 Technological roadmap of First Solar from cells results objectives to module objectives[14].

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.

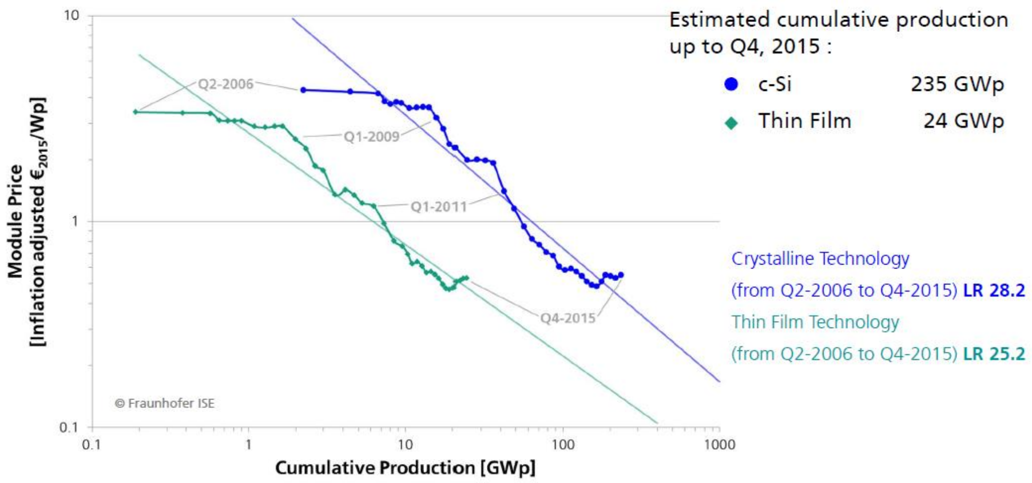


Figure 10 Learning curves for the prices of PV modules comparing CdTe technology (mainly First Solar) and c-Si technology[15].

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.

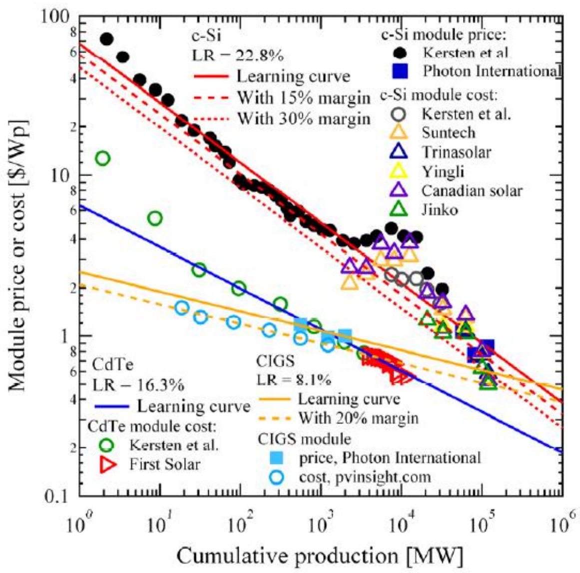


Figure 11 Learning curves and extrapolation carried out.

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.

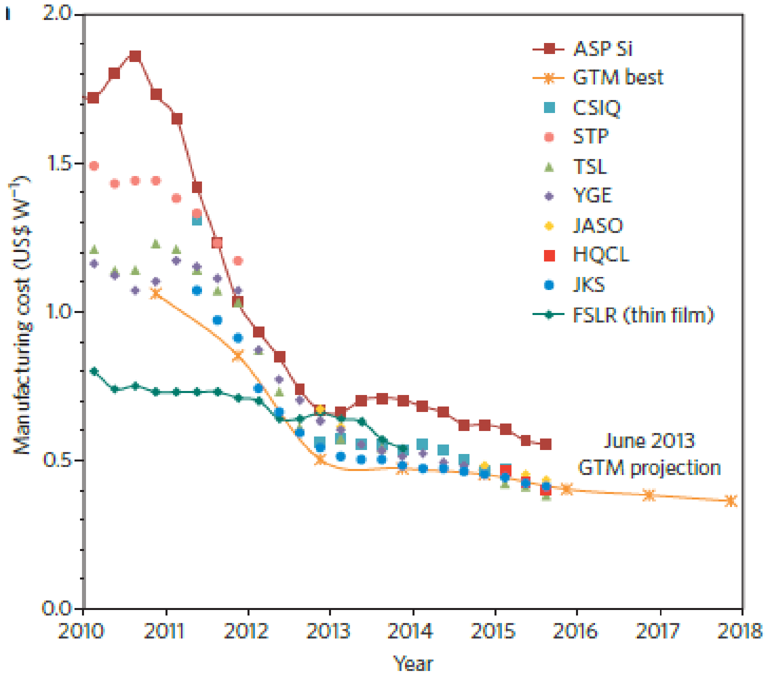


Figure 12 Evolution of module manufacturing costs presented as a function of the c-Si suppliers and for a thin film manufacturer (First Solar)[13].

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.

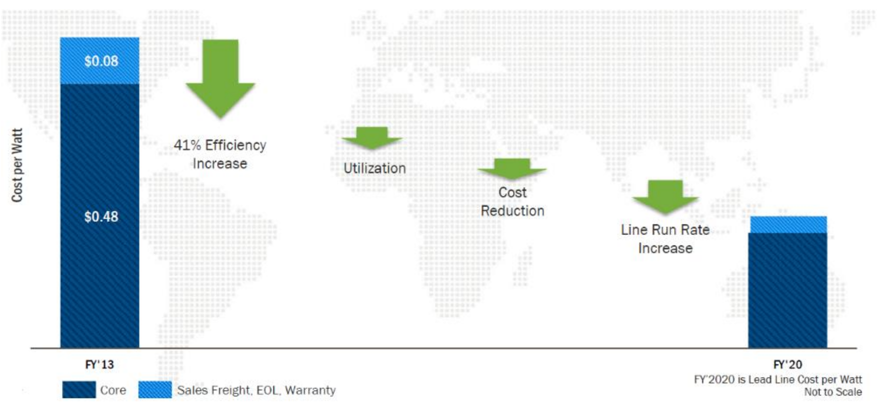


Figure 13 First Solar's module cost reduction until 2020.

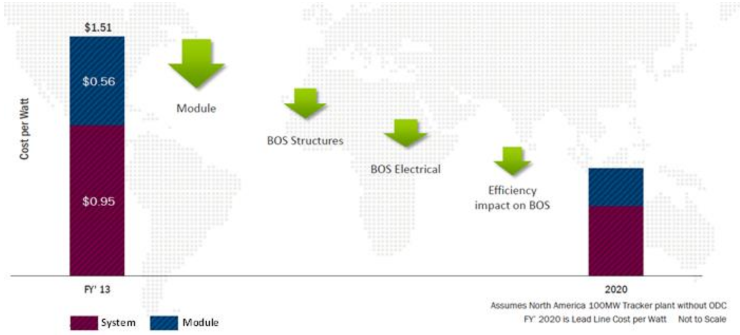


Figure 14 First Solar's plant cost reduction until 2020.

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 m²

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

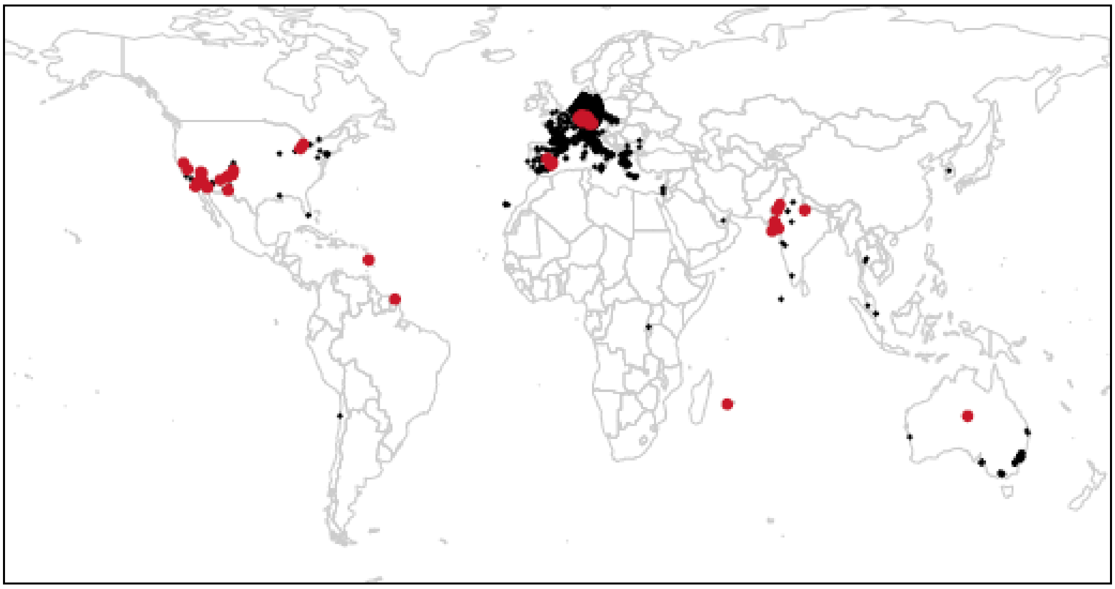


Figure 15 Location of First Solar power plants (black dot) and field reliability monitored sites (red dot)[19].

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.

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[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.-).

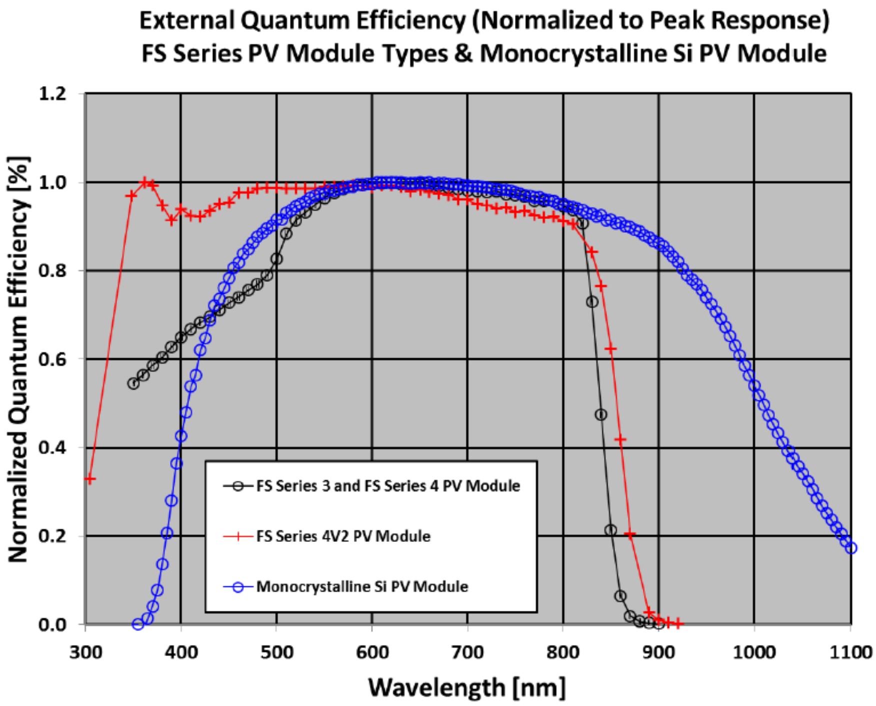

Figure 16 Normalized external quantum efficiency of First Solar FS Series 3, FS Series 4 and FS Series 4V2 CdTe PV module types compared with that of a single-crystalline Si PV module[23]. The specific properties of CdTe outdoor performance can be directly derived from its characteristic spectral response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

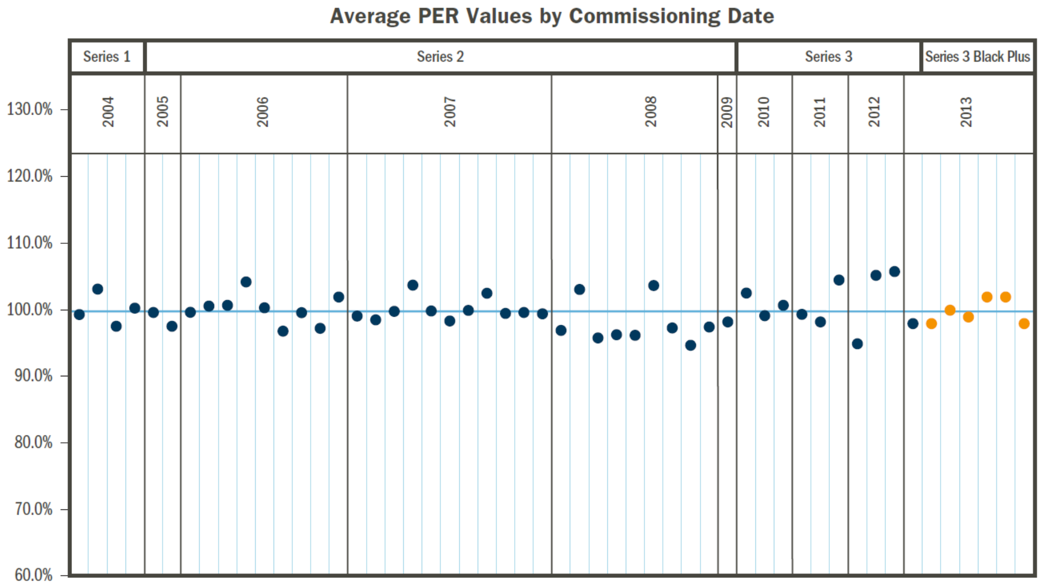

Figure 17 Average Predicted Energy Ratio (PER) by commissioning year for 270 MW of thin-film CdTe PV systems using First Solar modules: >270 MW monitored installations base, including >130 MW of hot-climate deployments[34]. Orange dots highlight the performance of the production series (S3 black plus) 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/m^2 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/m^2 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/m^2 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.

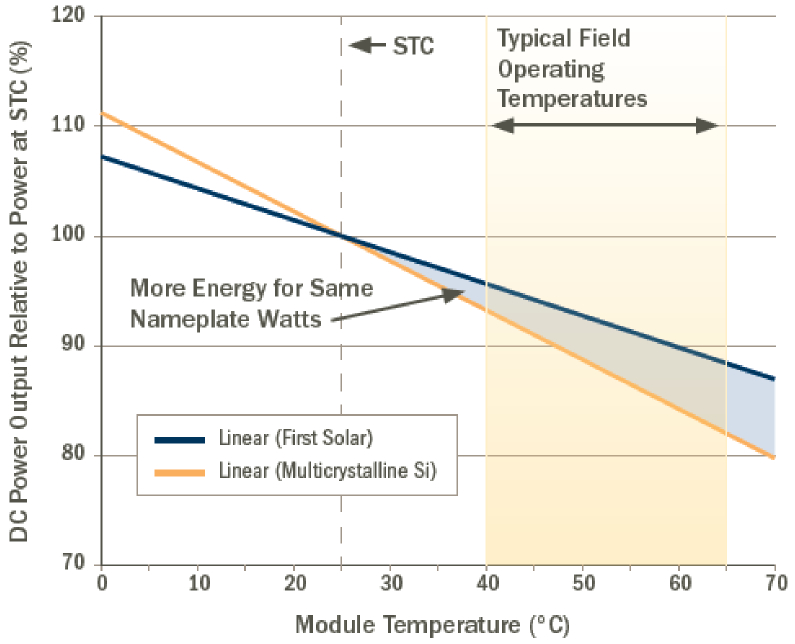

Figure 18 Comparison between the temperature dependence of CdTe modules with respect to multicrystalline silicon. First Solar's Series 4 and 4A temperature behavior (blue line) and standard multi c-Si modules (orange line) versus module output power (First Solar Series 4 data sheet) modules[37].

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.

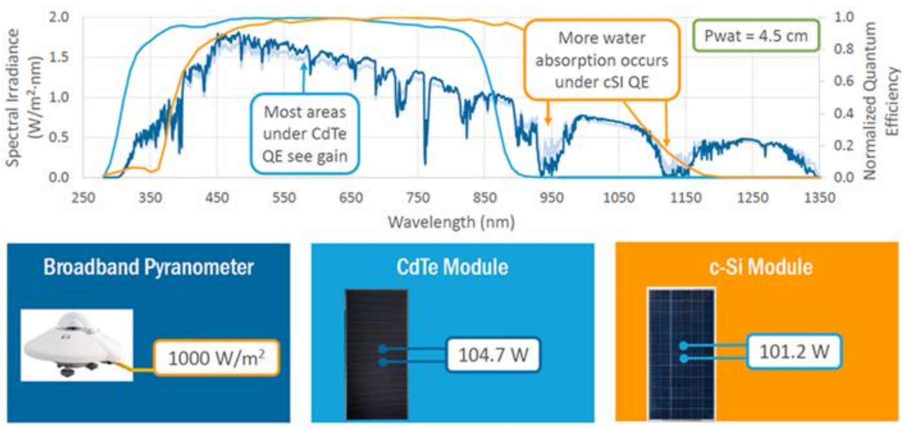

Figure 19 Effect of spectral changes related to the humidity level on the power output of CdTe modules compared to Si modules.

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).

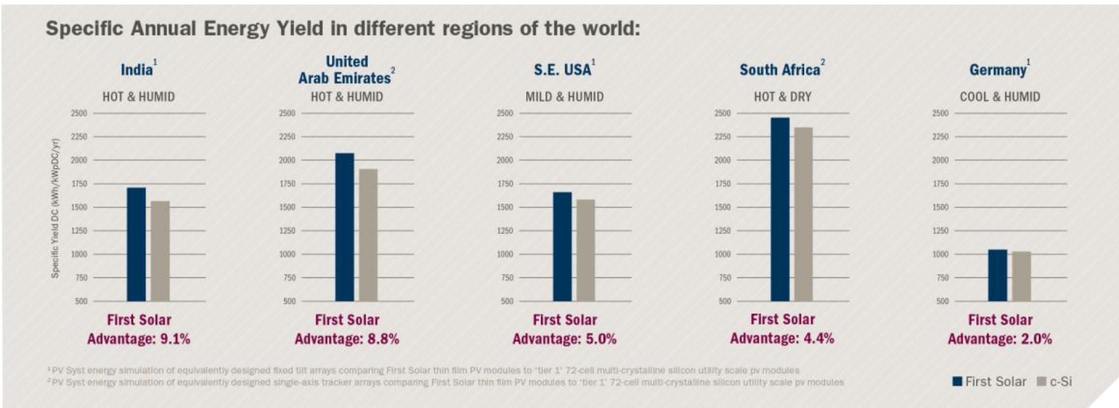

Figure 20 Energy yield of CdTe modules as a function of the location and local climate in comparison with Si multicrystalline modules.

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].

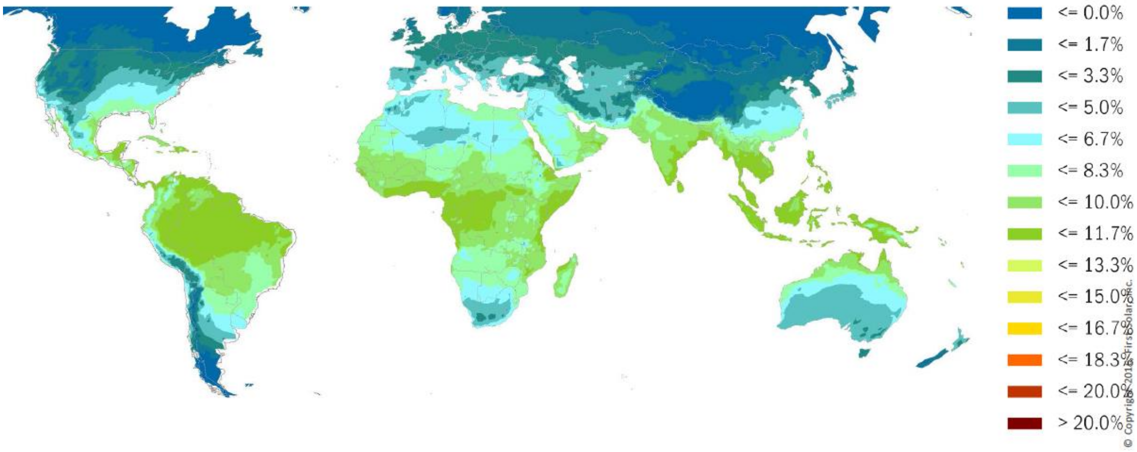

Figure 21 Effect of location on the comparison between the energy yield of CdTe First Solar Modules and multicrystalline Si modules.

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).

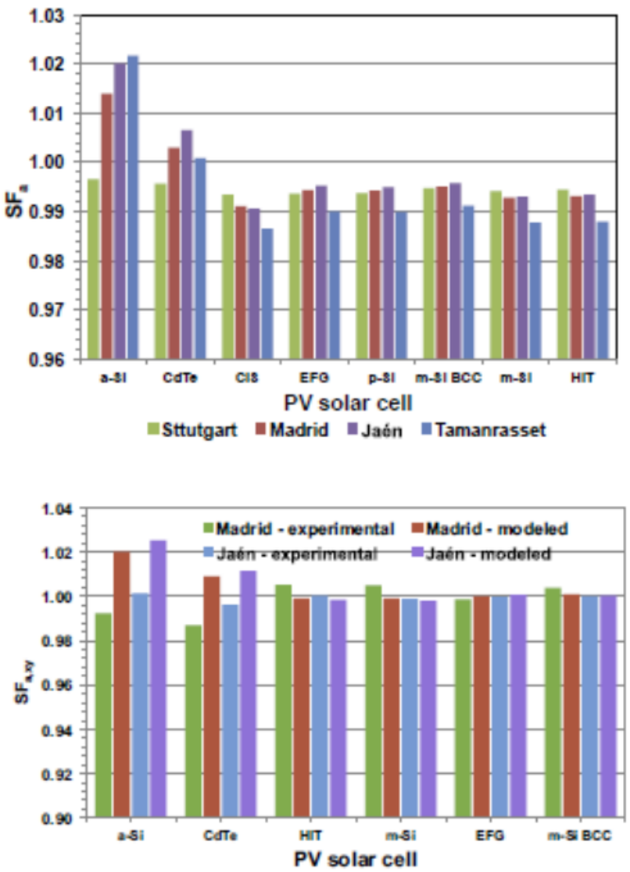

Figure 22 Top: Modeled figures of the spectral factor for different technologies and locations. Bottom: Experimental and modeled figures of the spectral factor for different technologies and two locations in Spain[42].

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.

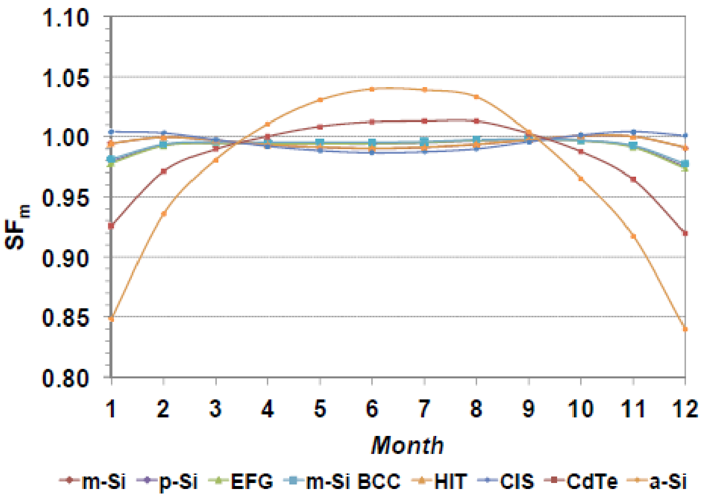

Figure 23 Modelled data of the spectral factor for the different technologies in Stuttgart[42].

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.

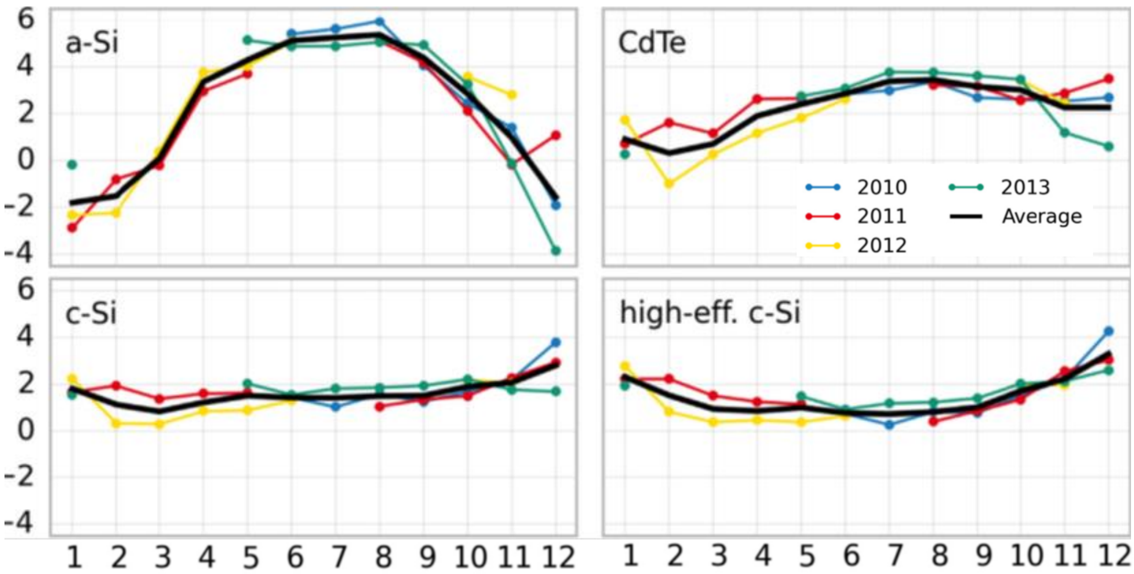

Figure 24 Monthly Spectral impact of PV technologies over 3 years measurements made in Freiburg (Germany)[45].

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 3^{rd} 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 39^{th} 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].

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[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.

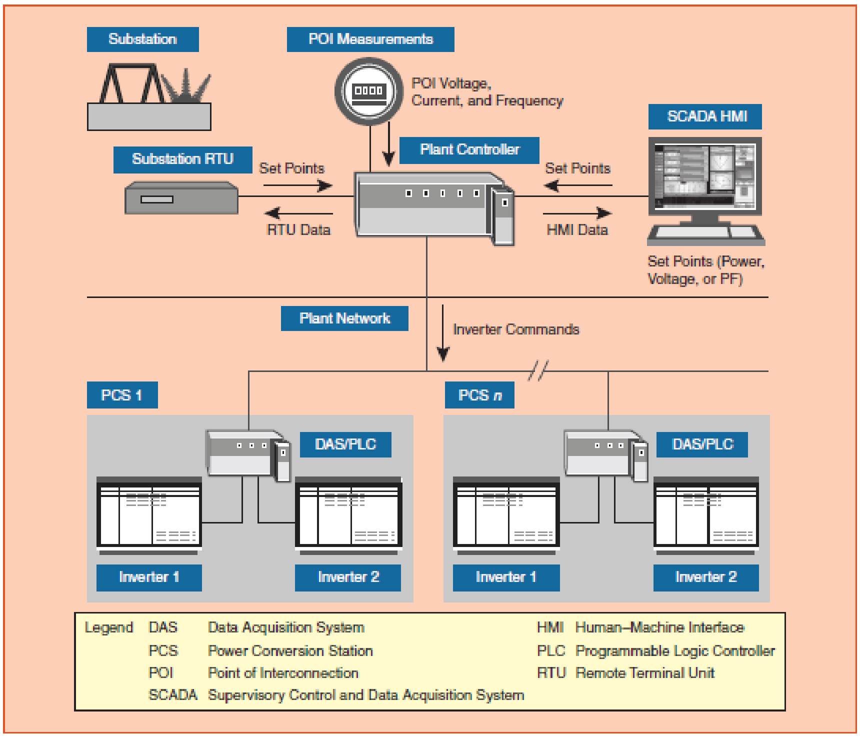

Figure 28 Example of a plant control system and interfaces to other components[68].

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 (3.74×10^2 $kg^{-1} \cdot m^3$) than for Cd(II) (3.3×10^4 $kg^{-1} \cdot m^3$) .

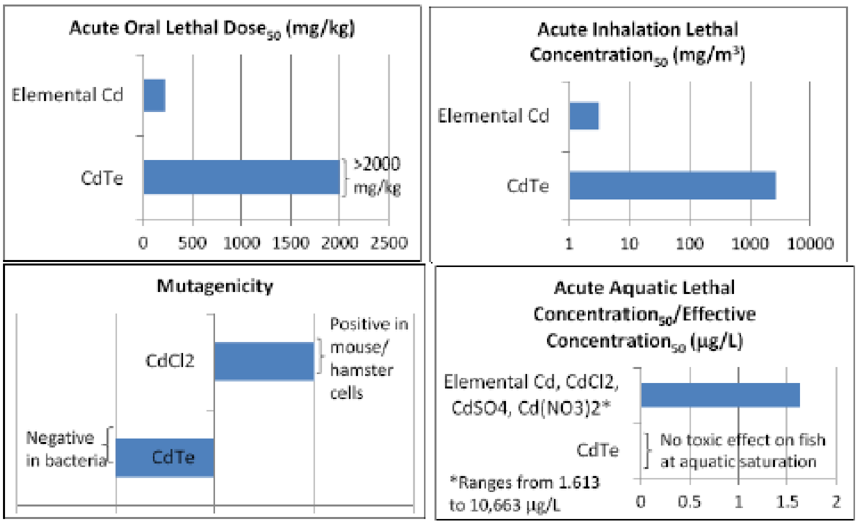

Figure 30 Comparative toxicity between Cd, other Cd compounds and CdTe.

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.

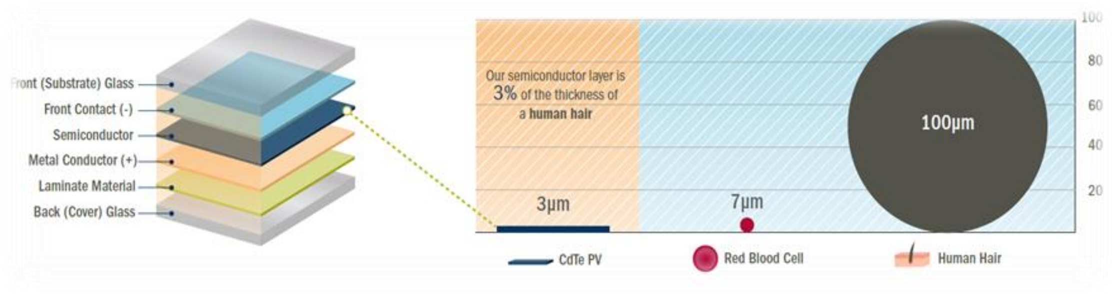

Figure 31 Schematic representation of First Solar's module architecture[76].

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.

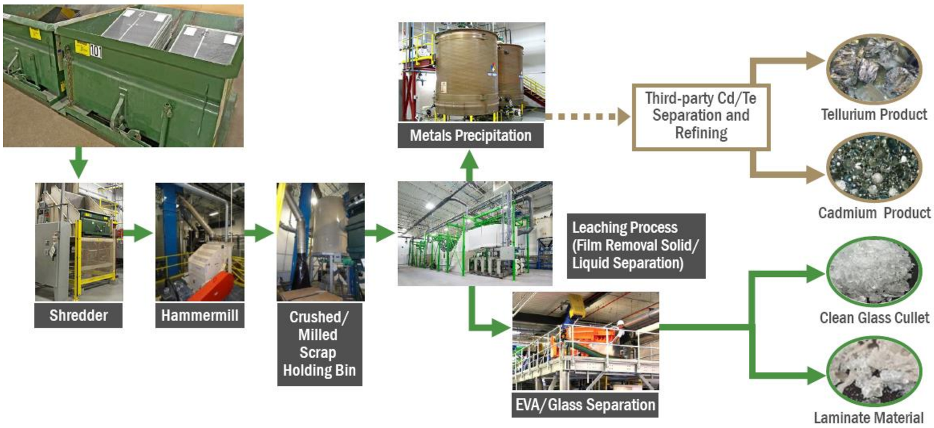

Figure 32 Flow chart of CdTe PV module recycling process[78].

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 µg/m^3 and 3.33 µg/m^3 for 8 hours and 12 hours exposure respectively. First Solar action limit is set at 1 µg/m^3 for its U.S. and Malaysia facilities and the actual indoor air values range from (0.006 to 0.35)[81] µg/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 µg/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.

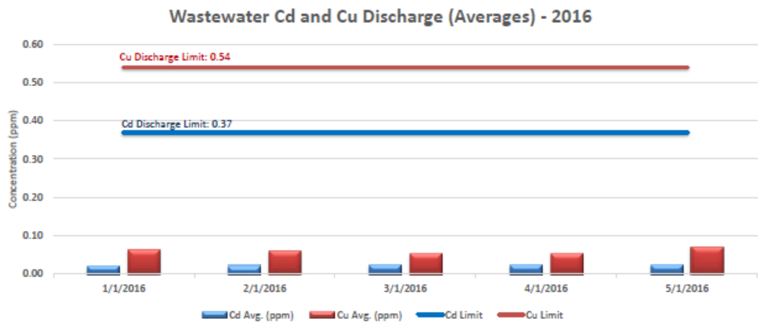

Figure 33 Wastewater Cd and Cu concentration[78].

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% $\pm$ 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) 0.0% (to solid residue)
	Gas burner 150 kW	20 minutes	0.7% (to air) 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) 0.0% (to solid residue) 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.

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[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.

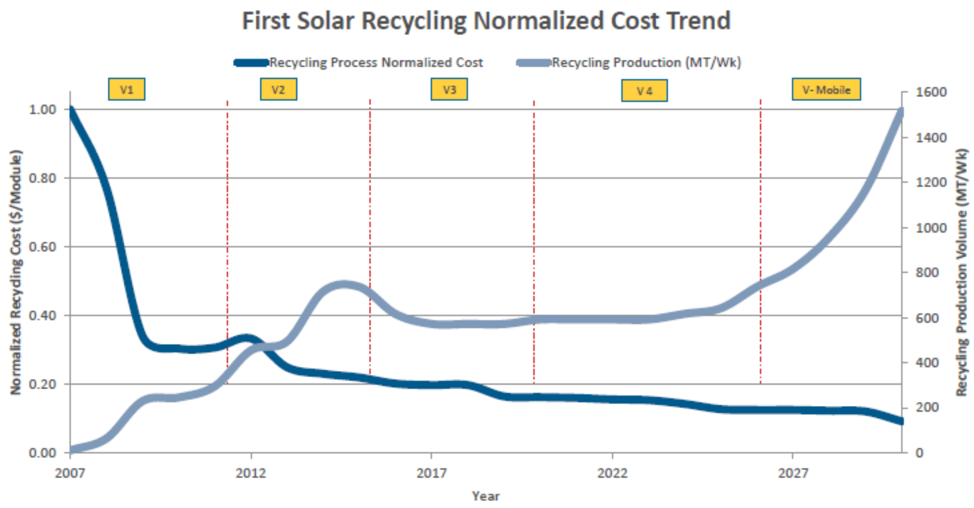

Figure 34 First Solar's recycling normalized cost trend[113].

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;
- η_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 / η_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 η_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.

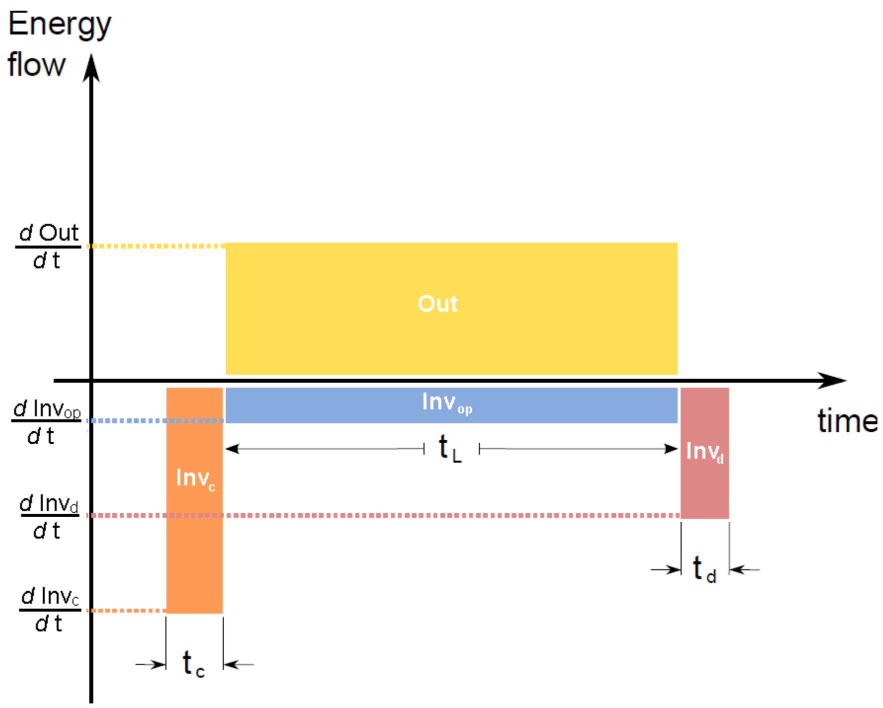

Figure 35 Schematic depiction of the energy 'investments' (**Inv_c** + **Inv_{op}** + **Inv_d**) and of the energy 'return' (**Out**) of a PV system. The individual areas are drawn for illustrative purposes only, and are not intended to be quantitatively representative of a typical CdTe PV system.
Source: 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 $\mathbf{EROI_{PE\text{-}eq}}$ 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]:

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

- **Energy Pay-Back Time**

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

  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 ($\mathbf{EROI_{PE\text{-}eq}}$), 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[145b]	G	14.0%	1,331	30	73%	0.48	-	-	30
Wyss *et al.*, 2015[145b]	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 (**$EROI_{PE-eq}$**), 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 (**η_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 (η_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}]	$EROI_{PE\text{-}eq}$ [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 (**$EROI_{PE\text{-}eq}$**), 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 **η_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).

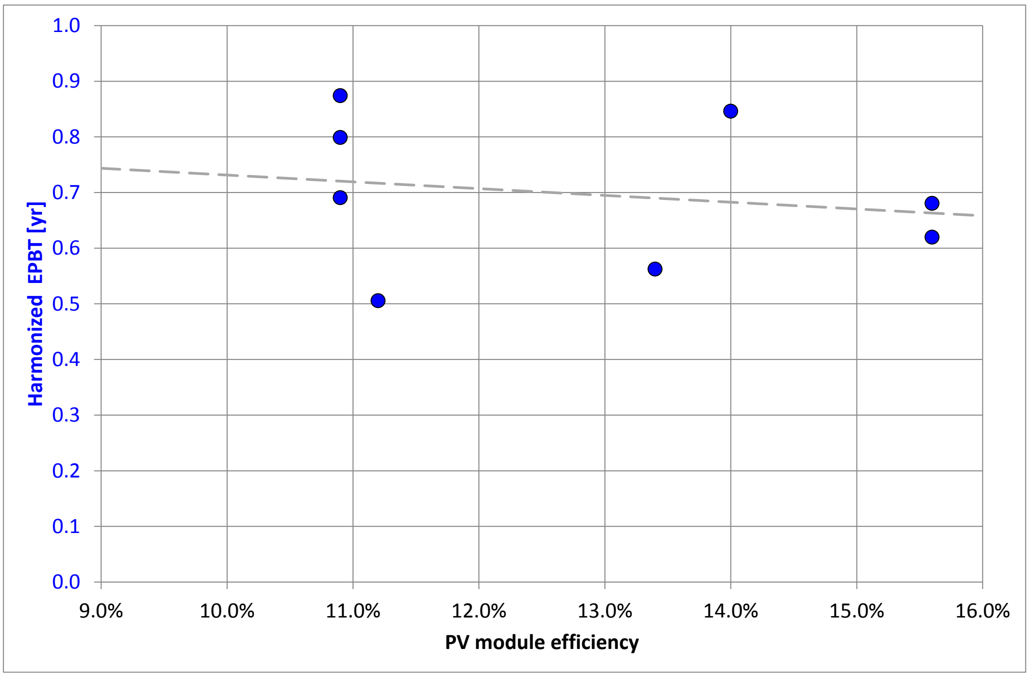

Figure 36 Energy Pay-Back Time (**EPBT**) of ground-mounted CdTe PV systems, *vs.* increasing PV module efficiency; all values harmonized to **T = 30** yr, **PR = 0.8**, **Irr = 1,700** kWh/(m^2·yr) and **η_G = 0.31** (data from Table 8).

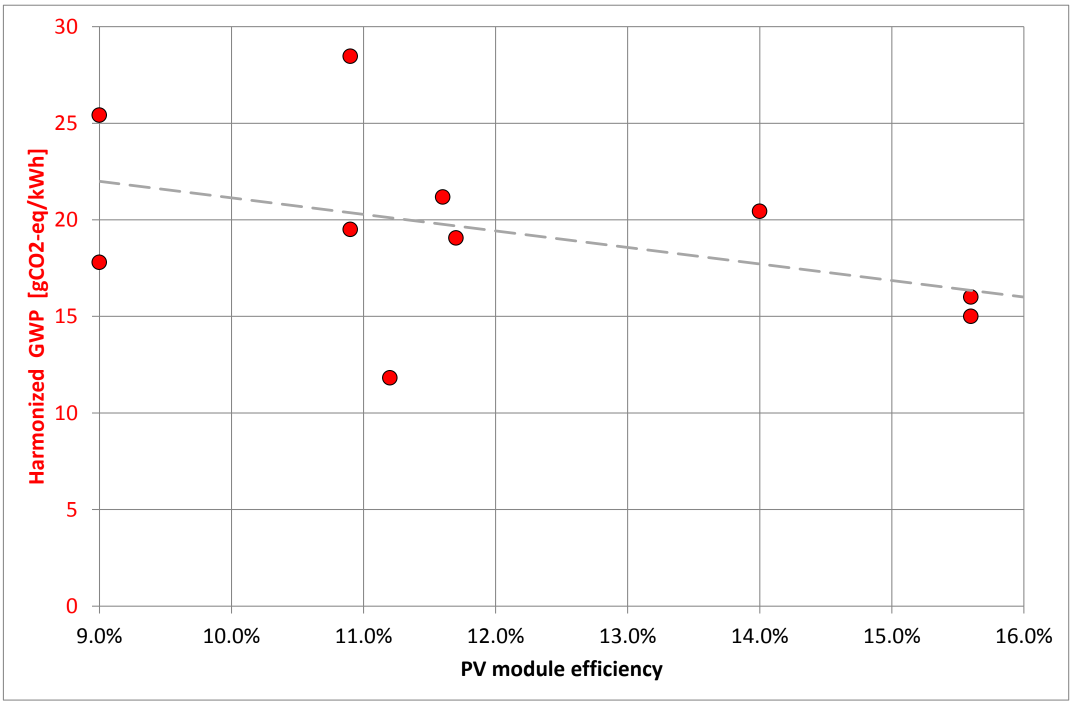

Figure 37 Global Warming Potential (**GWP**) for ground-mounted CdTe PV systems, *vs.* increasing PV module efficiency; all values harmonized to **T = 30** yr, **PR = 0.8**, **Irr = 1,700** kWh/(m^2·yr) and **η_G = 0.31** (data from Table 8).

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].

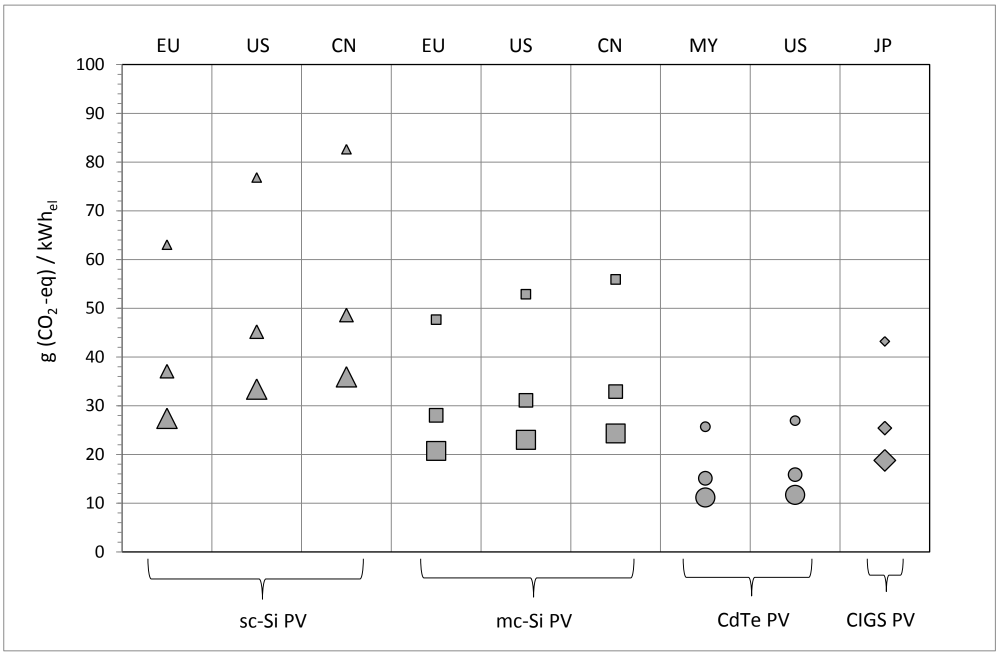

Figure 38 Global Warming Potential (**GWP**) of ground-mounted PV systems under three different irradiation levels[146].
Small symbols: 1,000 kWh/(m²·yr); medium symbols: 1,700 kWh/(m²·yr); large symbols: 2,300 kWh/(m²·yr).
EU= European Union; US= United States of America; CN= China; MY= Malaysia; JP=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

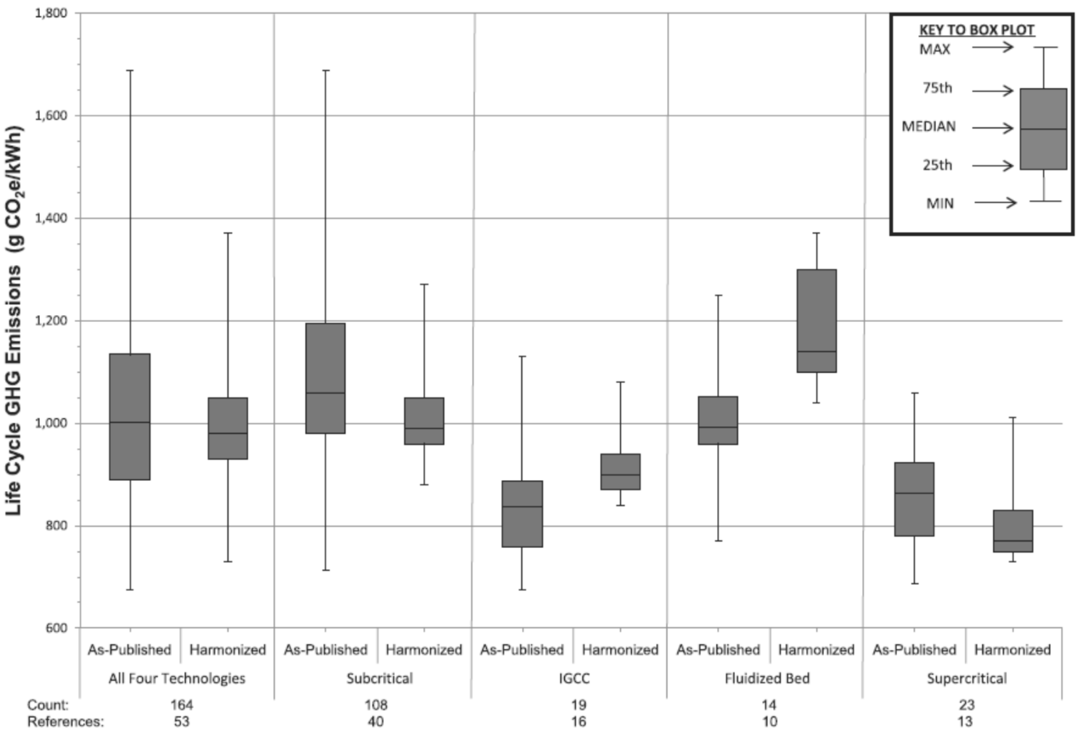

Figure 39 Global Warming Potential (**GWP**) of coal-fired electricity[150].
IGCC = Integrated Gasification Combined Cycle.

[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.

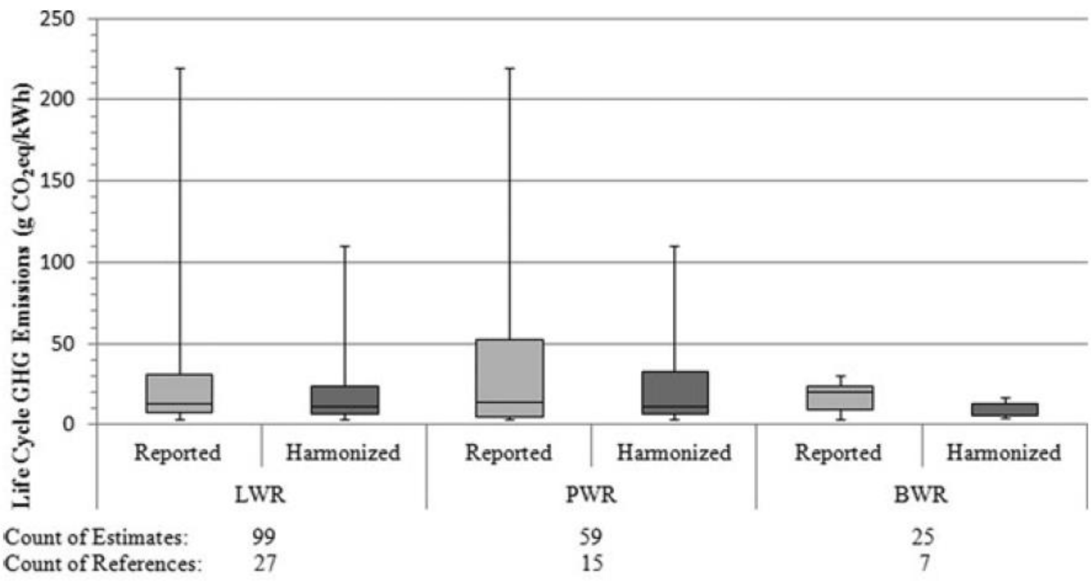

Figure 40 Global Warming Potential (**GWP**) of nuclear electricity[151].
LWR = Light Water Reactor; PWR = Pressurised Water Reactor; BWR = Boiling Water Reactor.

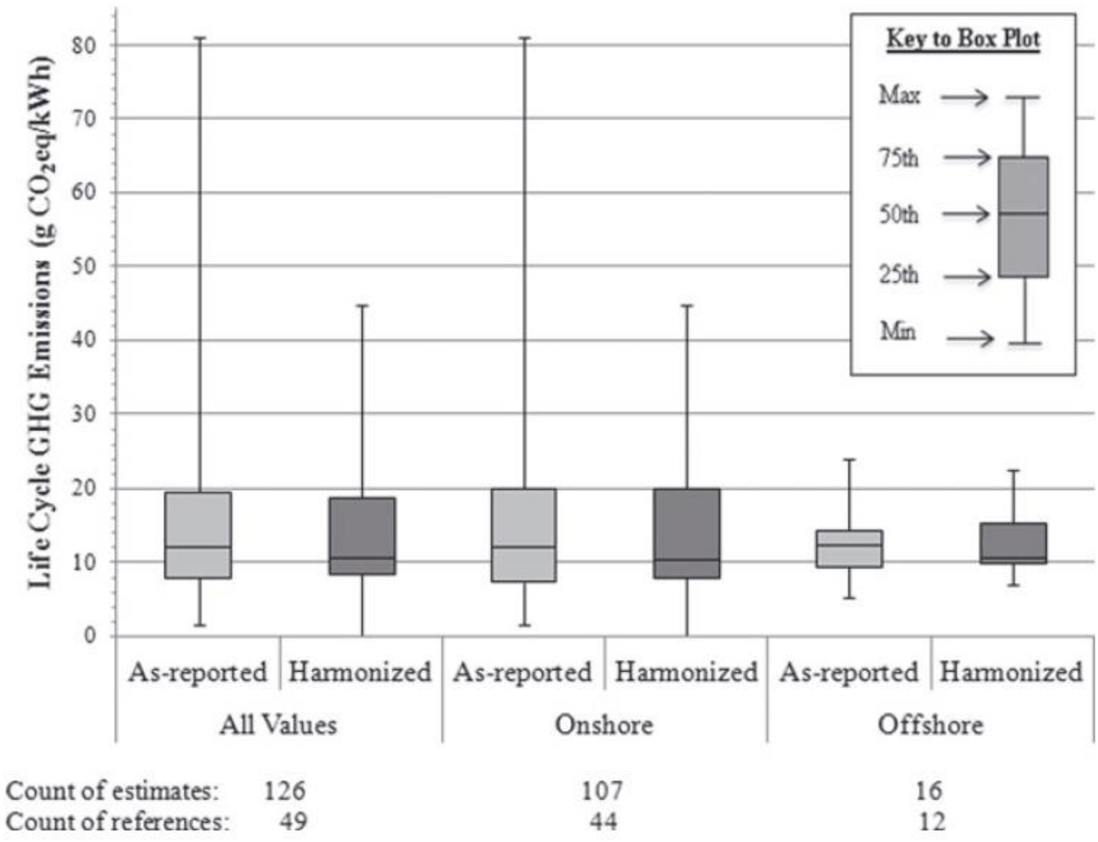

Figure 41 Global Warming Potential (**GWP**) of wind electricity[152].

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.

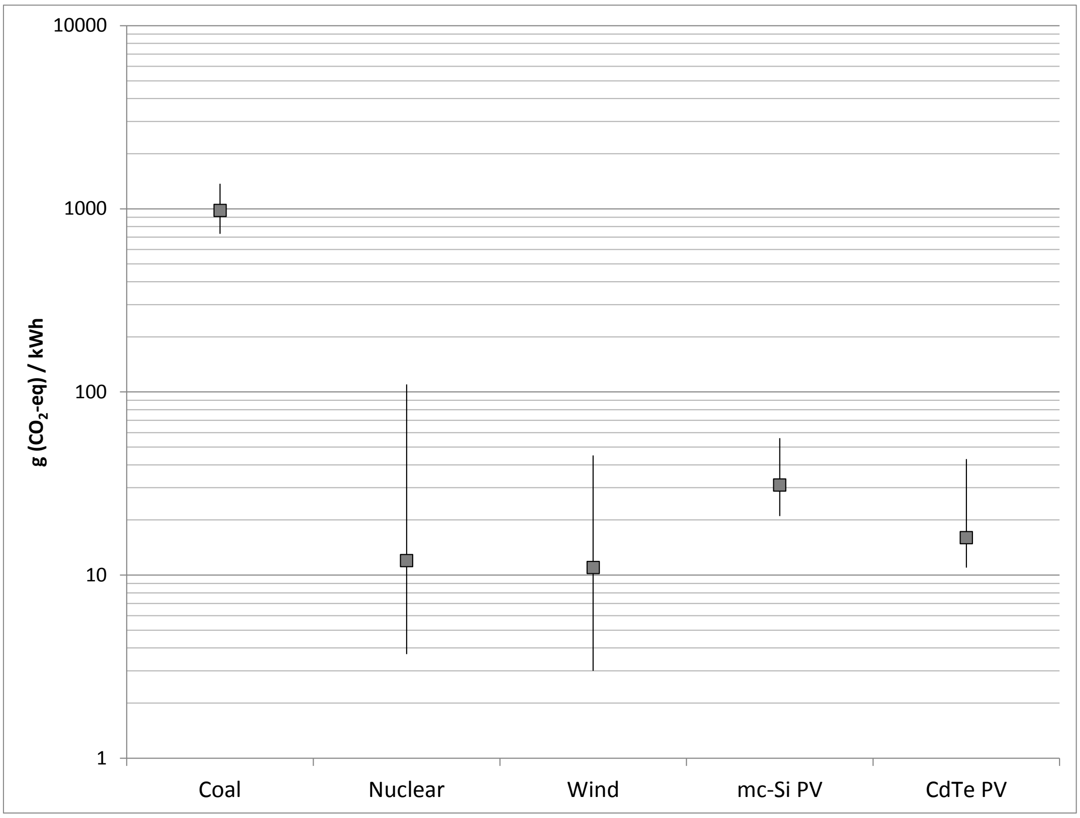

Figure 42 Minimum, maximum and median harmonized literature values for Global Warming Potential (**GWP**) of coal-fired, nuclear, and wind electricity, compared to latest values for mc-Si PV and CdTe PV electricity[146], respectively for **Irr** = 1,000 kWh/(m^2·yr), **Irr** = 2,300 kWh/(m^2·yr) and **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 75th 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

[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.

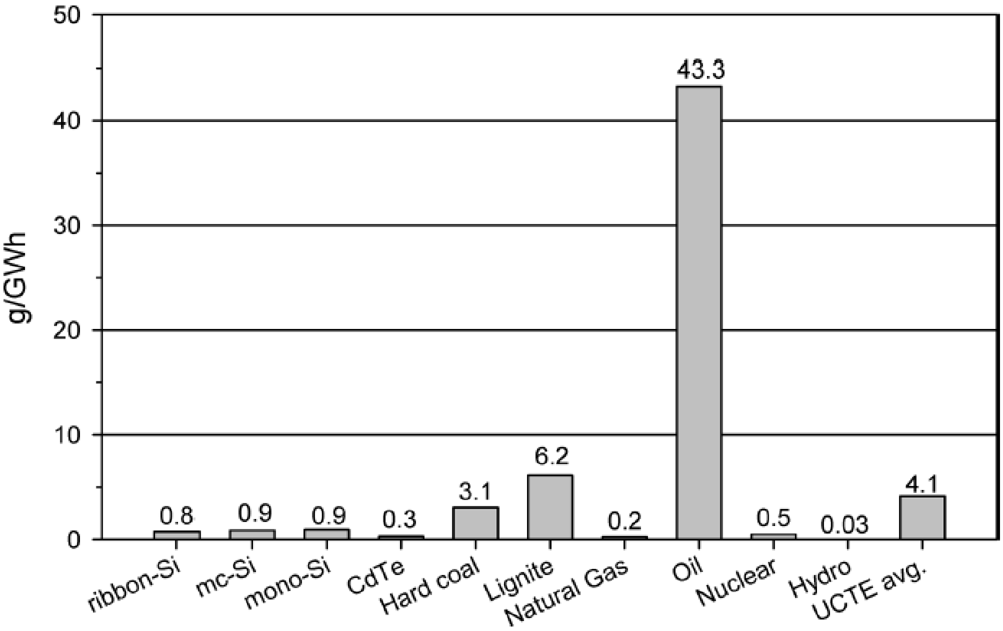

Figure 43 Life-cycle Cd emissions of electricity generation technologies[159].
Assumptions for CdTe PV are **η = 9%**, **T = 30** yr, **PR** = **0.8** and **Irr** = **1,700** kWh/(m^2·yr).

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.

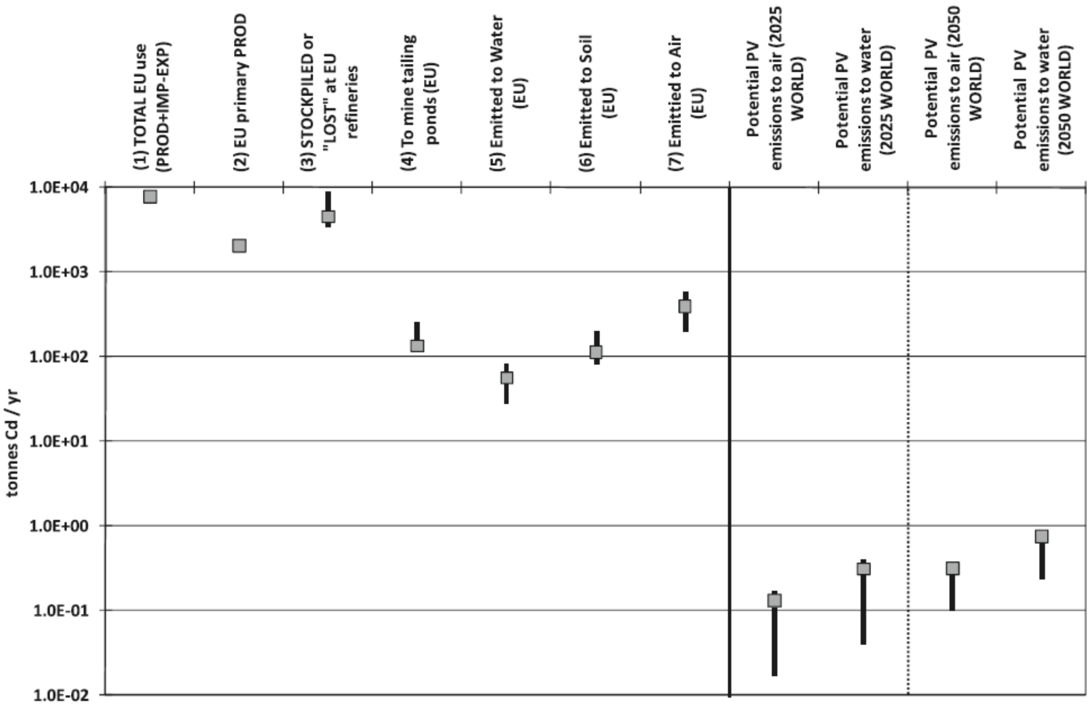

Figure 44 Current Cd flows in EU-27 compared to potential future global Cd emissions caused by CdTe PV (logarithmic scale)[153]. Assumed maximum cumulative capacities are 260 GW_p in 2025 and 1 TW_p in 2050.

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 [($km^2\cdot$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.

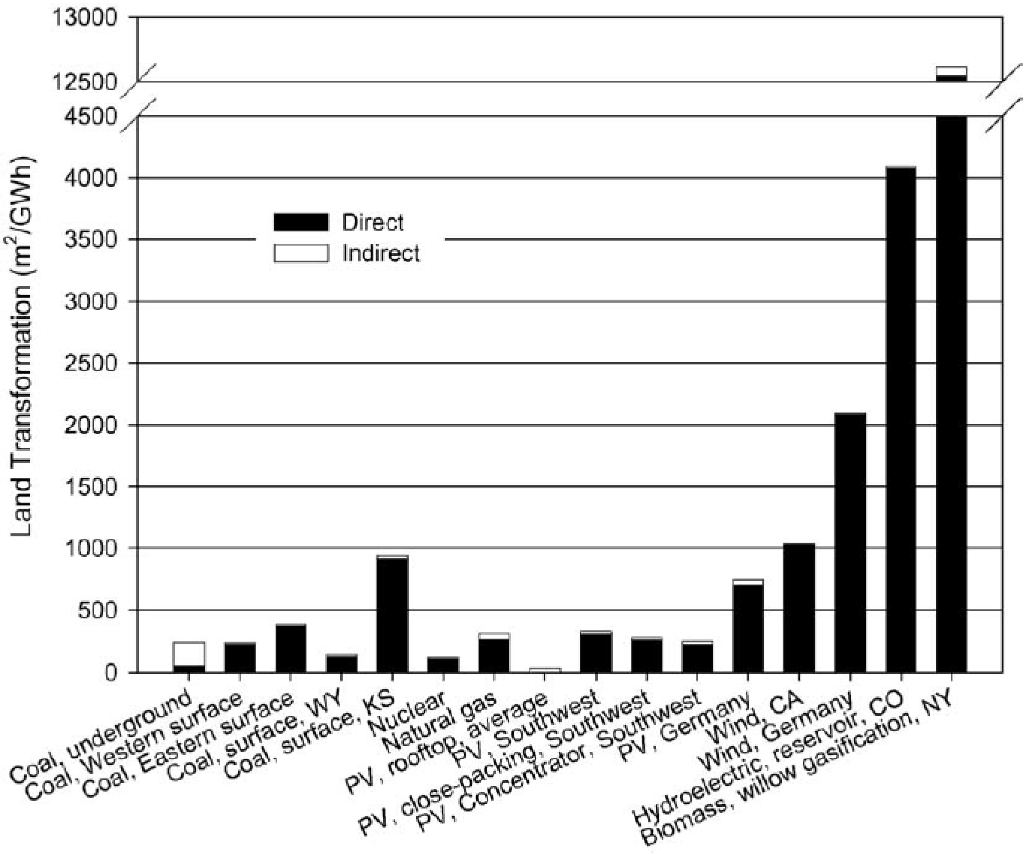

Figure 45 Land transformation for a range of electricity generation technologies[173]. Assumptions for PV are **η = 13%**, **T = 30** yr, **PR** = **0.8**, **Irr** = **1,800** kWh/(m^2·yr) for "rooftop, average", and **Irr** = **2,400** kWh/(m^2·yr) for "Southwest".

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.

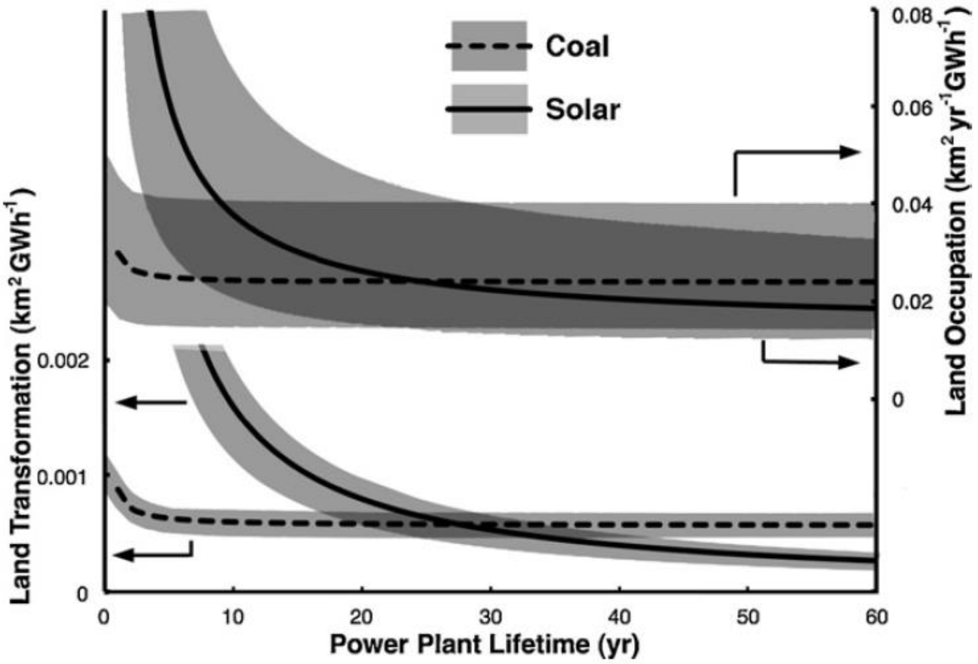

Figure 46 Land transformation and land occupation for PV and coal-fired electricity[174].
Assumptions for PV are **η = 13%**, **PR** = **0.8**, **Irr** = **1,700** kWh/(m^2·yr).

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,

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[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).

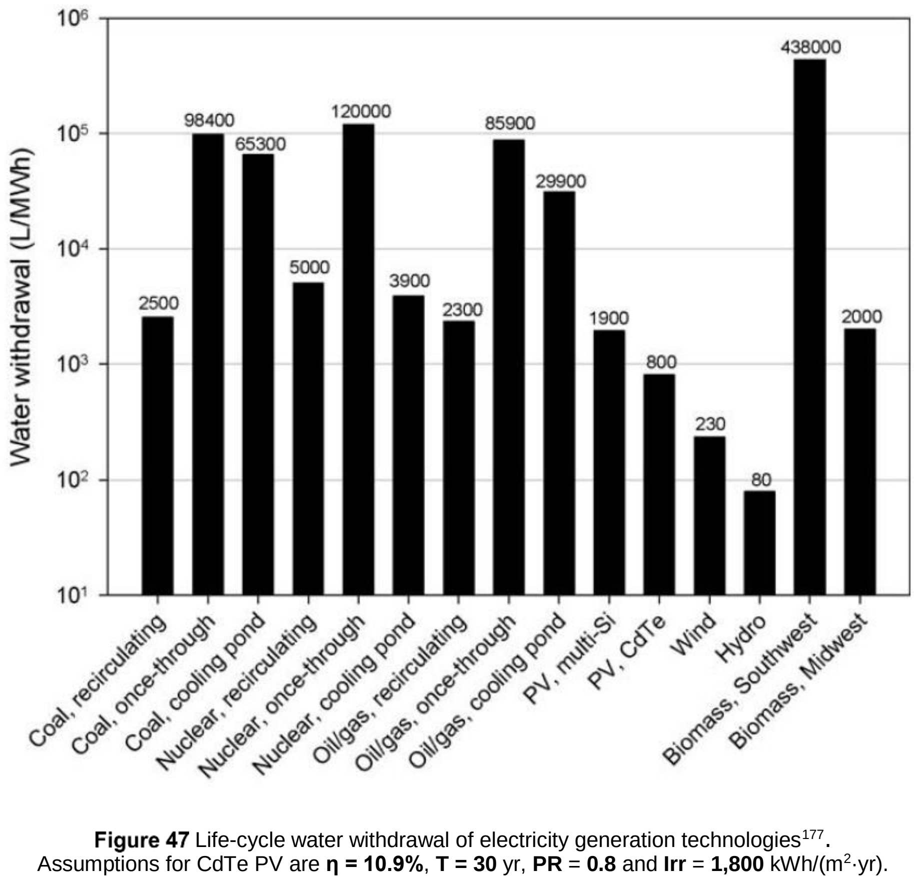

Figure 47 Life-cycle water withdrawal of electricity generation technologies[177].
Assumptions for CdTe PV are **η = 10.9%**, **T = 30** yr, **PR** = **0.8** and **Irr** = **1,800** kWh/(m^2·yr).

[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.

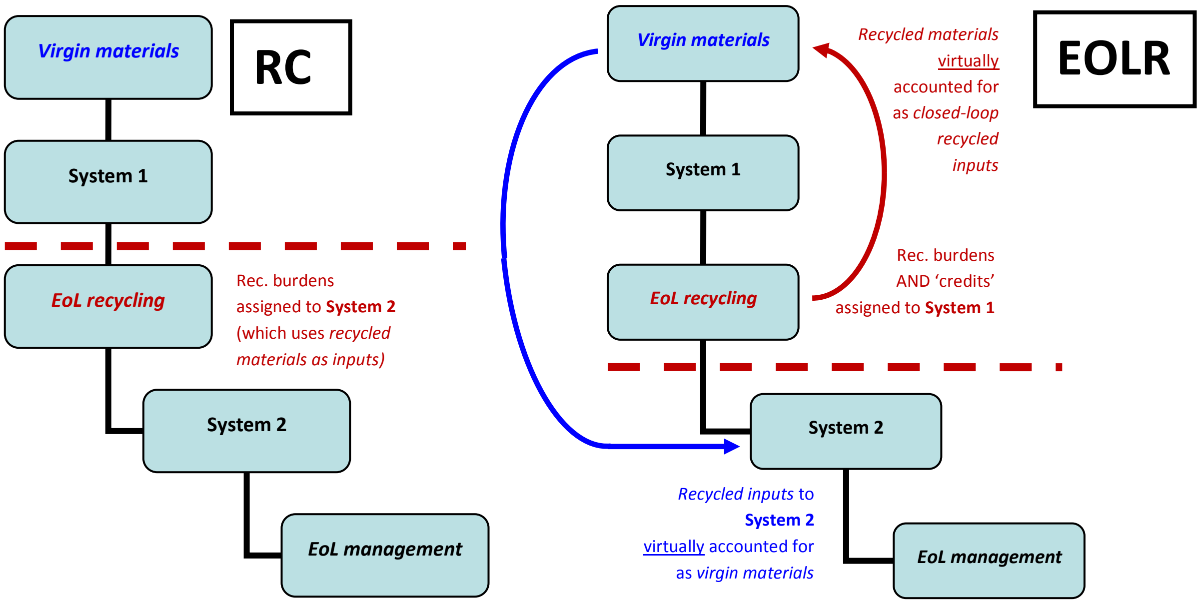

Figure 48 Alternative allocation options for the assessment of end-of-life (EoL) recycling.

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].

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[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

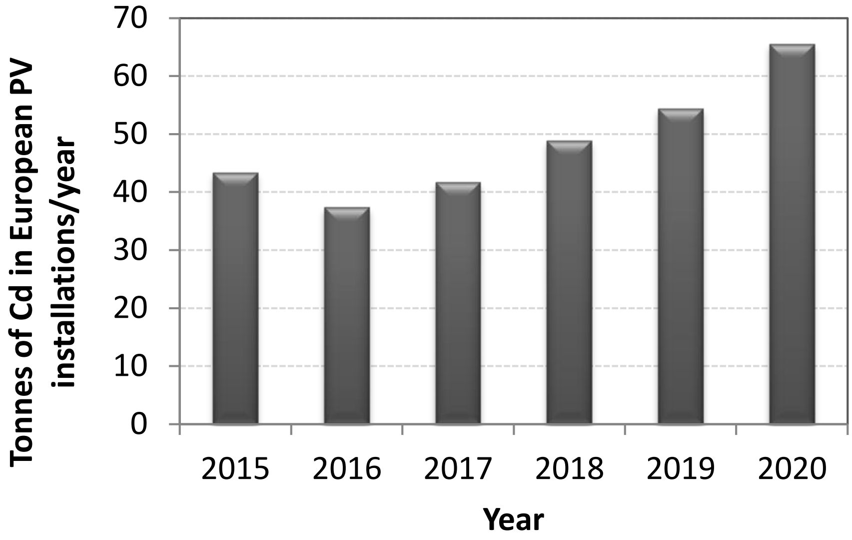

Figure 49 Calculated Cd mass expected to be employed yearly in European CdTe PV installations.

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.

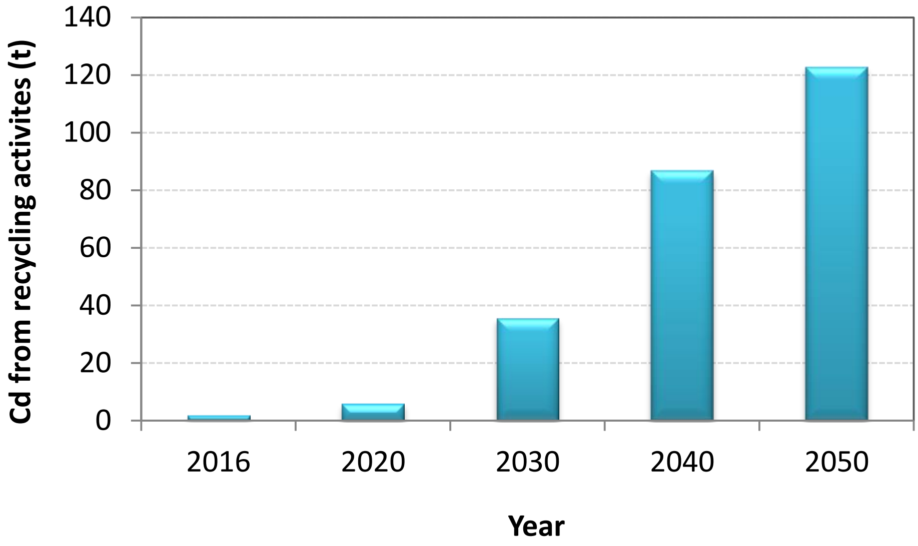

Figure 50 Calculated cumulative Cd recovered from the recycling of CdTe PV modules in Europe.

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.