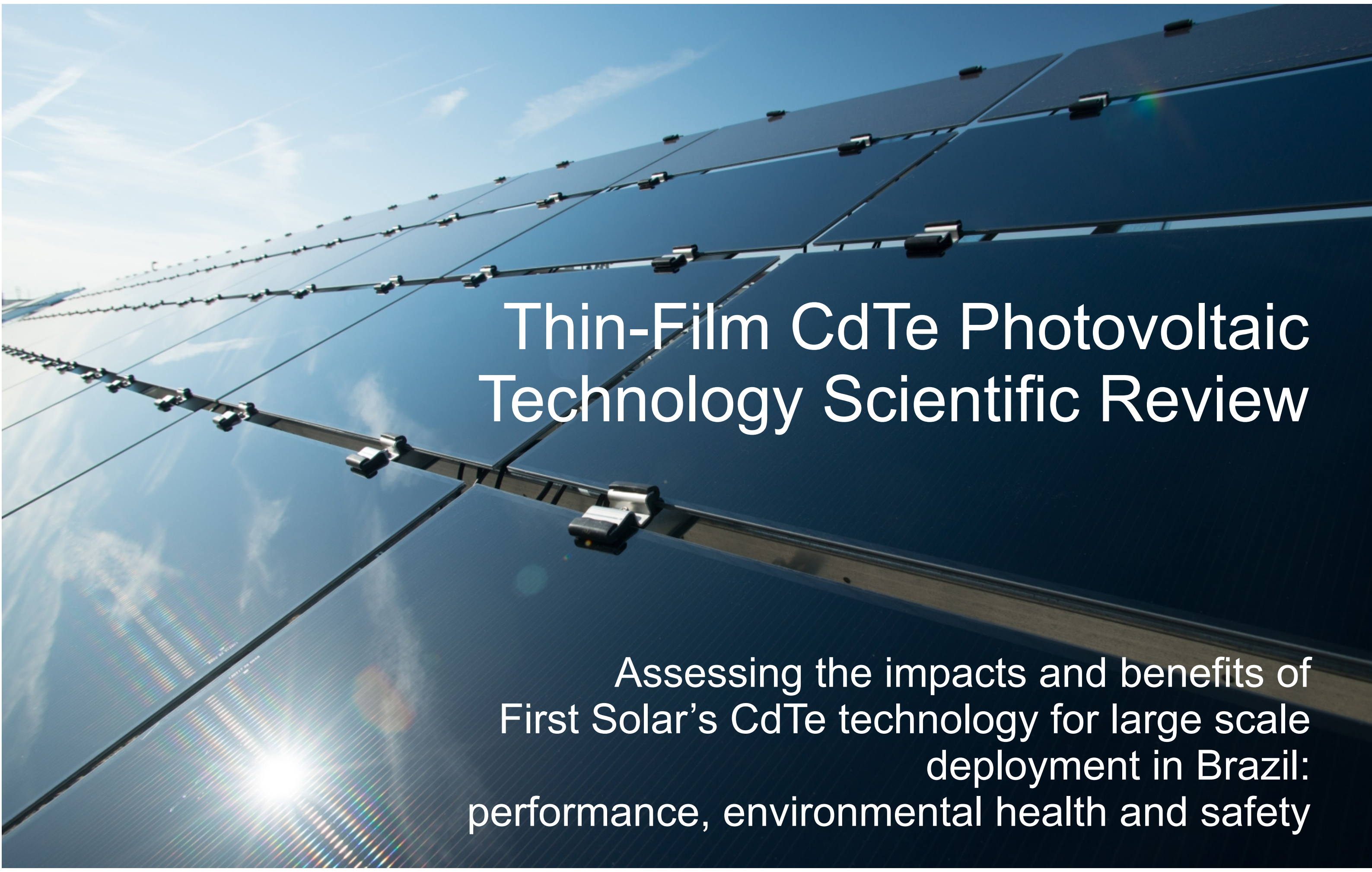
First Solar.



Thin-Film CdTe Photovoltaic Technology Scientific Review

Assessing the impacts and benefits of First Solar's CdTe technology for large scale deployment in Brazil: performance, environmental health and safety

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Executive Summary

Photovoltaic solar energy conversion (PV) is the direct conversion of sunlight into electricity. PV is currently the fastest-growing energy technology worldwide [1], and there are a number of different PV technologies in the market. With the tremendous cost-reductions experienced by this industry in recent years, PV generation has consistently grown at nearly 55%/year over the last five years, and is becoming cost-competitive with many of the conventional and large-scale electricity generation technologies. Among the commercially-available PV technologies, thin-film Cadmium Telluride (CdTe) has demonstrated consistent year-on-year developments in both cost-reduction and efficiency improvements.

This scientific review of the *CdTe photovoltaic (PV) technology: Impacts and benefits of First Solar's CdTe technology for large-scale deployment in Brazil including the performance, environmental, health and safety assessment,* covers issues related to both the large-scale manufacturing and large-scale field deployment of thin-film CdTe PV devices in grid-connected power plants in Brazil[1]. An extensive and independent review of the published literature was carried out in order to assess whether the production and use of CdTe PV modules and systems introduces environmental, health or safety risks to individuals under normal operating conditions and foreseeable accidents at any stage of fabrication, transportation, installation, utilization, decommissioning or recycling. The review includes information obtained from publicly available literature and studies carried out by third parties, information obtained directly from CdTe PV module manufacturer First Solar, as well as information gathered during a site visit to First Solar's manufacturing plant in Perrysburg-OH in the USA in September 2014.

Compared with other PV technologies available in the market, the lower temperature coefficient of power of CdTe PV renders it a better performer under the high operating temperatures prevailing in the field, especially in warm and sunny countries like Brazil. The study also compares the potential deployment of large-scale CdTe solar power plants with the most relevant commercially-available PV technologies, as well as with other more conventional electricity generation technologies, with emphasis on large-scale hydropower generation. Hydroelectricity generation is by far the major source

[1] Worldwide, utility-scale PV (i.e., power plants larger than 5 MWp) has been the fastest-growing sector of the PV market since 2007, and since 2012 has accounted for the largest share of the overall PV market in terms of new MWp installed [http://emp.lbl.gov/reports/re]. In Brazil, utility-scale solar PV generation is only now getting started, with the first of the so-called solar auctions carried out by the Brazilian government on 31st October 2014. In this first solar auction, a total of 31 solar farms, with a total nominal capacity of 1,048 MWp of PV, were contracted.

of electricity in Brazil (> 70%), and electricity consumption in the country has increased more than 5%/year over the last 40 years, reaching 473 TWh in 2014 [2]. The report shows that despite being area-intensive, PV power plants can generate more electricity per occupied area than large hydropower plants operating in Brazil[2]. The Itaipu[3] hydropower plant is an emblematic example of how well PV generation compares with hydroelectricity production in terms of land use. If the 1,350 km^2 surface area of the Itaipu lake were covered with 15% efficient CdTe First Solar[4] PV modules side by side, this gigantic PV plant would be rated at over 200 GWp (instead of the 14GW nominal power of the Itaipu hydropower plant), and would be able to generate over 240 TWh/year under the irradiation conditions where Itaipu is located. Furthermore, if the 40,000 km^2 of all the Brazilian hydropower plant flooded areas combined were covered with 15% efficient PV modules side by side, the total installed PV capacity would be close to 6 TWp (6,000 GWp). If a conservative average annual PV energy generation yield of 1,200 kWh/kWp/year is assumed for the combined regions where all these hydropower plants operate, around 7,200 TWh of solar electricity could be produced annually. This is over ten times more than the current annual electricity consumption in Brazil, more than what was consumed in the USA (4,274 TWh in 2013) or China (5,023 TWh in 2013), and around one third of all the annual electricity consumption of the whole planet [2]! These impressive figures are presented to give a rough idea of the potential of PV solar power plants in Brazil, and compared with the total accumulated installed PV capacity on the whole planet (reaching close to 170 GWp at the end of 2014), demonstrate that despite its huge potential, there is still a long way until a more widespread use of PV technology results in solar electricity becoming a major contributor to the Brazilian or worldwide energy mix. One last comparison that can be made between hydropower and solar power generation in Brazil is related to the complementary nature of the water and solar resource availability (e.g., high solar irradiation in times of draught). Many of the large Brazilian hydropower plants are seasonally water constrained, depending on the particular year's rain pattern, whereas PV requires little to no water to operate [3,4]. 2014 brought the first national energy auction with a specific category for solar power, and also the worst draught in eight decades in the Brazilian Southwest. The combined impulse of these two events can make 2014 a turning point for solar PV development in Brazil: results of the first solar auction held in the country, which contracted

[2] More than 10% of the total world installed hydropower capacity of some 1,000 GW are installed in Brazil. The total flooded areas of these 104 GW of hydropower operating in Brazil is in excess of 40,000 km^2 (http://www.aneel.gov.br/aplicacoes/capacidadebrasil/energiaassegurada.asp).

[3] Until 2014, the Itaipu (14 GW generating capacity) dam in Brazil used to be the largest hydropower plant in the world in terms of annual electricity generation. While the Three Gorges (22 GW installed capacity) hydropower plant in China has a larger nominal rating, it has historically been the second largest operating hydroelectric facility in terms of annual energy generation, generating 98.1 TWh in 2012 and 83.7 TWh in 2013, while the annual energy generation of the Itaipu dam was 98.3 TWh in 2012 and 98.6 TWh in 2013 http://www.mme.gov.br/mme/galerias/arquivos/noticias/2014/Energia_no_Mundo_-_OIE_e_OIEE_-_Final.pdf. In 2014, due to unfavorable hydrological conditions, it was anticipated that Itaipu would lag behind Three Gorges.

[4] This report is based on 15% efficient First Solar Series 4 PV modules, released in 2014.

the first batch of large-scale PV solar plants in Brazil (total of 1,048 MWp) were announced on the same day when Itaipu Hydropower released information that, due mostly to water constraints, the largest Brazilian power plant has generated less electricity in 2014 than in previous years[5].

The carbon footprint of CdTe PV generation (CO_2 equivalent per MWh generated), as well as the Energy Pay-Back Time (EPBT) of CdTe PV are also presented in the study, and compared with other commercially-available PV technologies, as well as with large hydropower electricity production in Brazil. The EPBT is measured in years and represents the time a CdTe PV module or system should operate in the field in order to produce the amount of energy equivalent to fabricate the PV module or system. The lifetime CO_2-equivalent emission of a CdTe PV plant operating in Brazil is around 0.01 tCO_2/MWh (10 gCO_2/kWh), which is orders of magnitude lower than any of the current conventional electricity sources, including the Brazilian hydropower-dominated electricity generation mix [5-7]. A hydropower dam emits biogenic gases such as CO_2 and mostly CH_4, which is a powerful greenhouse gas (according to the IPCC, CH_4 is 25 to 72 times stronger a heat-trapping gas than CO_2, depending on the timeframe considered [8]). The amount of energy that a CdTe PV module or power plant will be able to generate in Brazil over its +25 years lifetime is up to 30 times larger than the energy required to produce that same PV module or solar power plant. The typical EPBT of CdTe in Brazil is shorter than one year, ranging from 0.82 to 0.94 years in the regions where utility-scale solar power plants will be installed, and 1.22 years at the least sunny sites in the country. Mono and multi-crystalline silicon PV modules operating in Brazil will also present a considerably larger carbon footprint (ranging from 30 to over 60 gCO_2/kWh) and EPBT (ranging from 1.82 to 3.07 years) than CdTe PV.

Heavy metal emissions is a sensitive topic, and the environmental, health and safety review also addresses this important issue, with extensive literature showing that CdTe is a solid and stable compound that is insoluble in water, is far less toxic than elemental Cd [9,10], and does not vaporize at the temperatures likely to be reached even if CdTe PV modules are exposed to a typical field fire. The European Chemical Agency (ECHA) does not classify CdTe as harmful if ingested or if in contact with skin, and CdTe PV modules pass the U.S. EPA's Toxicity Characteristic Leaching Procedure (TCLP) test, designed to assess the potential for long-term leaching of products disposed in landfills [11,12]. At end-of-life, discarded CdTe PV modules from solar power plants in Brazil should not be characterized as hazardous waste, if they are not finally disposed of in Brazil (e.g. transported outside of Brazil for recycling)[6]. In 2005 First Solar established a global and comprehensive

[5] http://www1.folha.uol.com.br/mercado/2014/11/1541888-itaipu-perde-lideranca-em-energia.shtml

[6] Under Brazilian law, waste containing Pb or Cd is listed as hazardous waste regardless of the volume of the chemical it contains (Brazilian Association of Technical Standards - *ABNT* by means of the normative *NBR*

collection and recycling program, in which over 90% of the semiconductor material and around 90% of the glass is currently recycled in facilities located in the USA, Germany, and Malaysia. With larger volumes, which are likely in future volume markets like Brazil, First Solar expects to reduce the transportation costs of the recycling process, and run mobile or in-country recycling facilities as a profitable part of the PV manufacturing business.

First Solar's efficiency roadmap has led to fleet average, best line average, and record PV module efficiencies of 15.4%, 16.2% and 18.6%, respectively through mid-2015, with prospects for more than 20% efficiencies in the near future, and close to 25% as a possible limit. Considering the better spectral response to the bluer spectra resulting from more humid climates, and the low temperature coefficient of power of CdTe (-0.25 to -0.34%/^{o}C, compared with -0.45 to -0.50%/^{o}C for crystalline silicon PV), the effective power conversion efficiency of CdTe at the higher operating temperatures prevailing in the field in Brazil is higher than that of the conventional silicon PV technologies. This will lead to more energy (kWh = revenue) generated for each unit of power (kWp = investment) installed.

The overall conclusion of this study is that CdTe PV is one of the most adequate solar energy generation technologies for the Brazilian climatic conditions, and that CdTe PV systems do not represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product, including recycling. CdTe PV provides a good combination of large-scale industrial processing and field performance, making it a cost-effective technology for utility-scale PV plants in Brazil. Expected efficiency improvements and cost-reductions shown in First Solar's roadmaps are likely to consolidate this position.

10004:2004). Since Pb and/or Cd compounds are commonly used in commercial PV modules including silicon PV [9], these modules are likely to be characterized as hazardous waste at end-of-life if disposed of in Brazil.

1. Introduction

Solar electricity or solar PV generation is the static and direct conversion of the photon energy contained in sunlight into electrical energy, with no moving parts, no noise and no emissions into the air. The photovoltaic effect was first reported in 1839 by French physicist A-E. Becquerel, but the first practical PV device designed for energy conversion was a silicon solar cell presented in 1954 by researchers from the Bell Telephone Laboratories in the USA, with a 6% conversion efficiency [13]. In 1958 the first solar cells went to space powering the US satellite Vanguard I [14]. Vanguard I was the fourth artificial satellite to be sent to orbit, and at that time satellites were equipped with primary batteries that would discharge and disable communication with Earth after a few weeks in space. The robustness and reliability of PV cells in space resulted in Vanguard I communicating with Earth for over 10 years, and this event has set the stage for photovoltaics powering most of the satellites orbiting our planet to date.

While PV has the potential of becoming a major source of renewable and sustainable electricity generation worldwide, this potential can only be realized if PV devices that will operate reliably in the field for 25-30 years can be mass-produced in square-kilometers per year, and at costs below US$ 100/m^2 [15]. In the 60 years that passed since the early days of > US$ 1000/m^2, cm^2-area single-cell PV devices that could only be afforded in space applications, to modern, < US$ 100/m^2, m^2-area PV modules for bulk-power production in terrestrial applications, considerable R&D efforts and budgets were involved. R&D on a considerable number of materials for solar cell device production, and on large-scale, large-throughput industrial processes was also carried out extensively worldwide, resulting in PV finally starting to become cost-competitive in a number of markets worldwide. Finally, on top of all the issues related to reliability, volumes and cost, PV will only be a truly sustainable and viable energy generating technology if all processes involved in producing, transporting, installing, operating, decommissioning and recycling of solar PV plants are associated with acceptable environmental, health and safety impacts.

1.1. Purpose and scope

First Solar has participated in 12 Peer Review Studies since 2003 [16-27], where specialists from the USA (2003), the European Union (2005), France (2009), Spain (2010), Japan (2012), Germany (2012), Italy (2012), India (2012), Thailand (2012), the Middle East (2012), China (2013) and Chile (2013) were invited to carry out literature reviews on the potential impacts of large-scale deployment of the thin-film CdTe PV technology. This study aims at presenting an independent overview of the thin-film CdTe PV technology currently produced by First Solar, assessing the performance aspects, and the Environmental, Health and Safety (EHS) aspects of CdTe PV systems over their entire lifecycle, including issues related to the carbon footprint of CdTe PV production and deployment, and the Energy Pay-Back Time (EPBT) of this thin-film solar PV technology. The report briefly presents the world PV market and the commercially-available PV technologies, and then describes First Solar's CdTe PV module production technology and cost roadmap. The literature review includes a comprehensive but concise study on raw materials, manufacturing and recycling processes involved in CdTe PV module production at First Solar. The report also addresses output performance aspects of CdTe PV generation vis-à-vis the more traditional and commercially-available solar PV technologies in a sunny and warm climate, and finally, it compares land use and greenhouse gas (GHG) emissions of CdTe PV generation with the large hydropower generation plants operating in Brazil.

1.2. The solar PV market: Commercially-available PV technologies for terrestrial applications

The commercial PV scene has always been dominated by bulk single (or mono) and multicrystalline silicon devices [28], and thin-film CdTe is currently one of the most serious competitors in terms of efficiency and production costs. Thin-film solar cells present basic advantages over their bulk crystalline counterparts in terms of materials utilization, mass production and integrated module fabrication, and this has been the driving force for their development since the early sixties [28]. For thin-film PV devices, of the many materials and device configurations studied, three material families have emerged and reached industrial production and commercialization: (i) amorphous and microcrystalline silicon alloys (a-Si and µc-Si); (ii) cadmium telluride-based devices (CdTe); and solar cells based on copper, indium, gallium and selenium ($CuInGaSe_2$ or CIGS). These thin-film material families constitute the so-called second-generation PV technologies. Third-generation PV cells include organic, Perovskite, quantum dot and photoelectrochemical solar cells at different stages of R&D and pilot production, but so far only the first-generation bulk crystalline silicon and the three above-mentioned second-generation PV technologies are commercially available in large-area, large-scale production.

There is a multitude of PV materials and technologies at different stages of R&D, pilot and commercial production worldwide. Figure 1 shows a classical chart created and regularly updated by researchers at the National Renewable Energy Laboratory in the USA, which includes all PV technologies' best research-cell efficiencies. Of immediate interest for terrestrial, utility-scale applications are the blue and green families of data points. Solid and open blue squares represent respectively the more traditional single and multicrystalline silicon PV technologies, which together accounted for 90% of the worldwide 2014 PV shipments of some 40 GWp. Green circles represent the thin-film PV technologies: a-Si and µc-Si; CdTe; and CIGS. Among these thin-film technologies, market share in 2014 was 23% for a-Si and µc-Si; 23% for CIGS, and 54% for CdTe. Figure 2 shows the evolution of the global PV market from 1997 to 2014. Figures 3 and 4 show respectively the evolution of the market share among these first- and second-generation PV technologies from the early 1980's, and the evolution of the market share among the thin-film PV technologies since the year 2000.

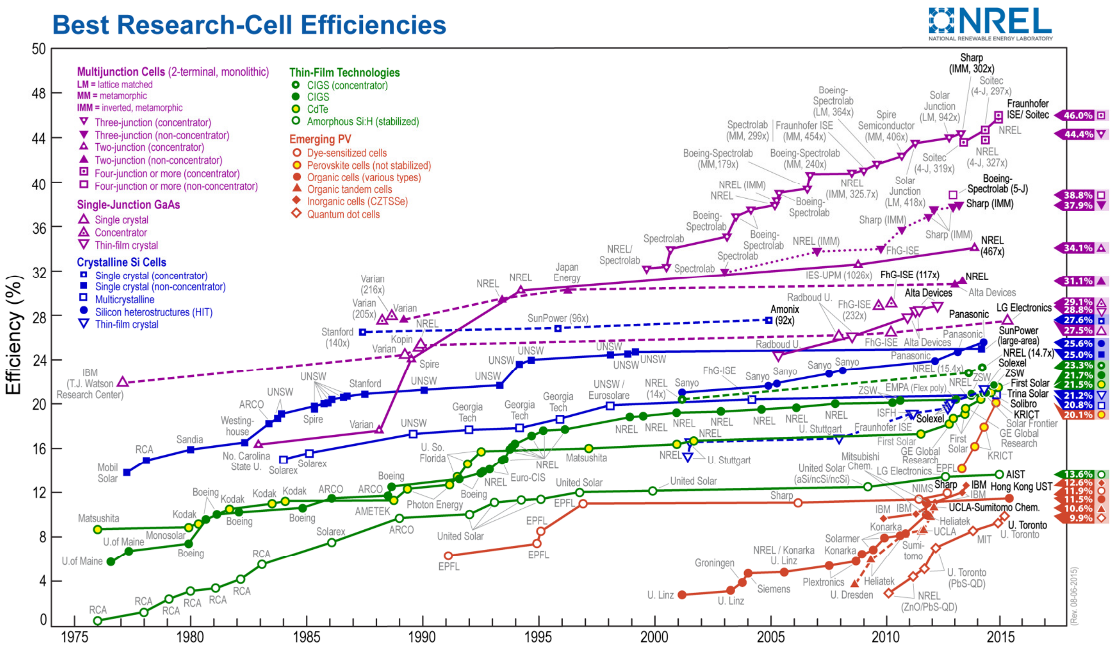

Figure 1: The National Renewable Energy Laboratory – NREL's solar cell efficiency chart [29] showing the evolution of the best research-cell efficiencies since the 1970's (updated June 2015).

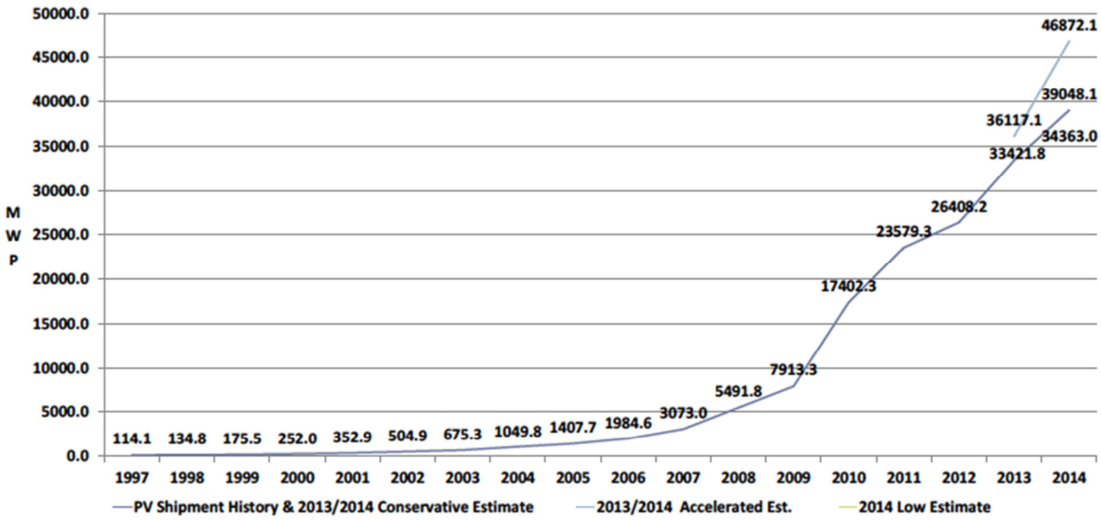

Figure 2: Global PV shipments from 1997 to 2014 [30]. With the PV incentive programs that were started with the establishment of the German feed-in tariff in the early 2000's, the global PV market reached the necessary scale for an effective cost-reduction that is still in course.

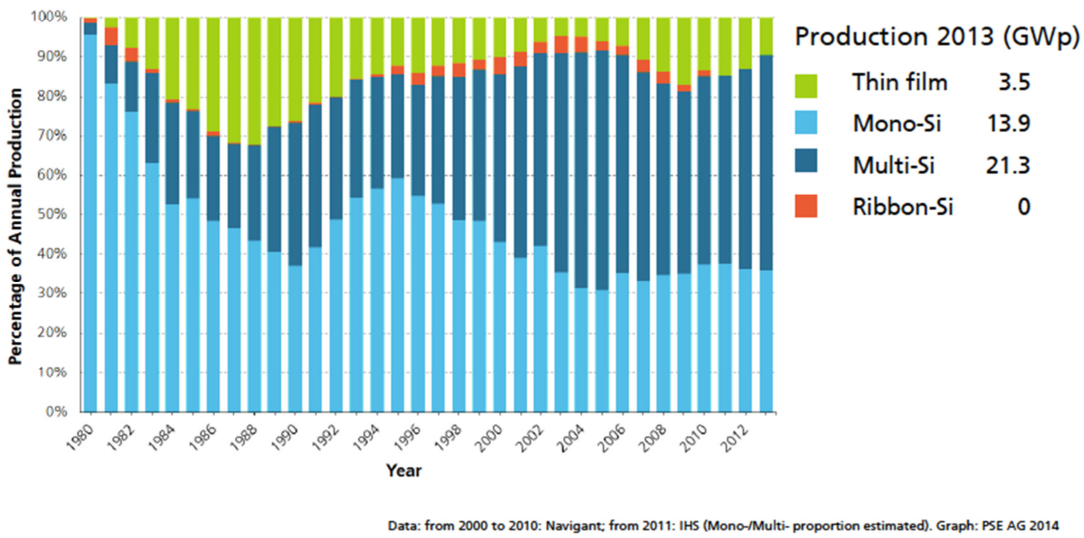

Figure 3: Evolution of the market share of first- and second-generation PV technologies from the early 1980's [31].

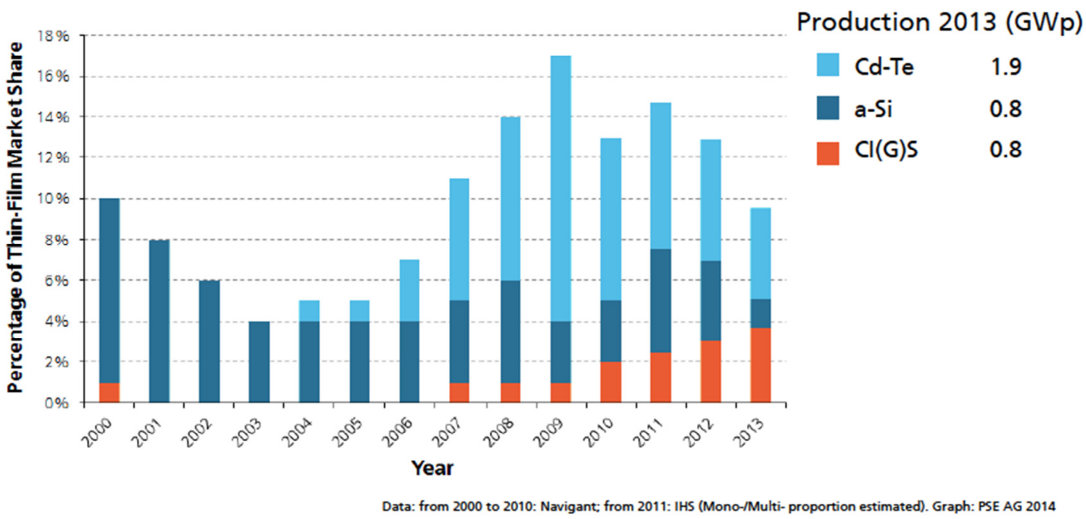

Figure 4: Evolution of the market share of second-generation thin-film PV technologies from the year 2000 [31].

Second-generation, or thin-film PV solar cells are typically a glass-glass laminate, with a very thin layer of active semiconductors, metal and oxide contacts sandwiched between these two glass panes. First Solar's thin-film solar cell structure is shown in Figure 5.

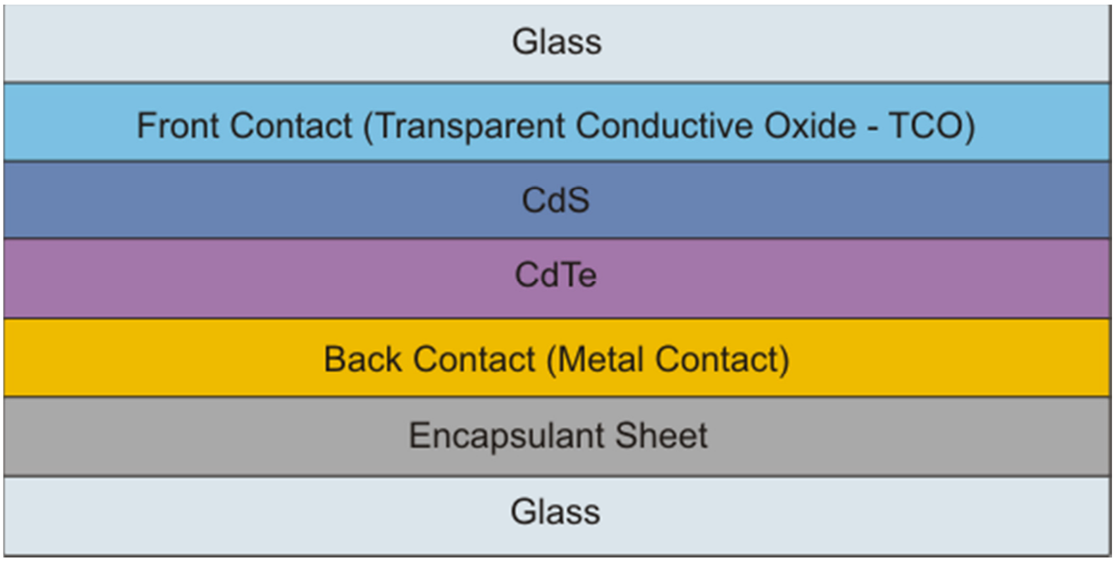

Figure 5: Schematic structure (layer thicknesses not to scale) of First Solar's thin-film CdTe PV devices, showing the active CdTe and CdS semiconductors, and metal and oxide (back and frontal) contacts sandwiched between two sheets of glass.

Research in CdTe dates back to the 1950's, after it was established that its band gap (~1.5 eV) almost perfectly matched to the distribution of photons in the solar spectrum in terms of conversion to electricity. A simple heterojunction design evolved in which p-type CdTe was matched with n-type CdS [32]. The cell was completed by adding top and bottom contacts. Early leaders in CdS/CdTe cell efficiencies were GE in the 1960's, and then Kodak, Monosolar, Matsushita, and AMETEK. In Europe, the development of thin-film CdTe solar cells started with the 6% efficient CdTe/CdS device presented by Bonnet and Rabenhorst in 1972 [33]. Much R&D was carried out to reach the present champion efficiency of 21.5% for a small-area single-cell device, and a 18.6% efficient full-size (0.72 m^2), 216-cell monolithic CdTe PV module, both produced by First Solar and independently confirmed [34]. The theoretical efficiency for a single junction CdTe/CdS solar cell is 33% [35]. Commercially-available CdTe is presently at the same efficiency level as multicrystalline silicon, and has the potential of reaching and even surpassing monocrystalline silicon efficiency levels in the future[7].

1.2.1. Temperature effects on PV system performance

All PV devices suffer output performance losses with increasing operating cell temperatures in the field. The negative temperature coefficient of power ($T_{coeff}P_{max}$) of first- and second-generation PV devices is shown in Table 1,

[7] R. Garabedian, "Technology Update," First Solar Analyst Meeting, 2014.

and the negative effects of field operating temperatures on power output are shown in Figure 6.

Table 1: The temperature coefficient of power (TcoeffPmax) of first- and second-generation PV devices (adapted from [36]).

PV Technology	bulk Si	a-Si/µc-Si	CIGS	CdTe[8]
$T_{coeff}P_{max}$, %/°C	-0.41 to -0.57	-0.10 to -0.30	-0.36 to -0.50	-0.25 to -0.34

For a maximal operating PV cell temperature of 65°C in the field, the temperature losses for a CdTe PV power plant will be in the order of 10%, while the crystalline silicon temperature losses will be around 18%.

Conversion efficiency is directly related to a PV power plant footprint, which is particularly important in utility-scale PV as it relates to land use, metallic support structures for ground-mounting of PV arrays, and copper wiring, which are part of the so-called Balance-of-Systems (BOS) costs. With the fast declining costs of PV modules, BOS costs are becoming dominant, and the current 15% efficiency of First Solar's CdTe, along with its low temperature coefficient on power, result in the same effective conversion efficiency level as that of multicrystalline silicon devices for operation in warm climates like Brazil.

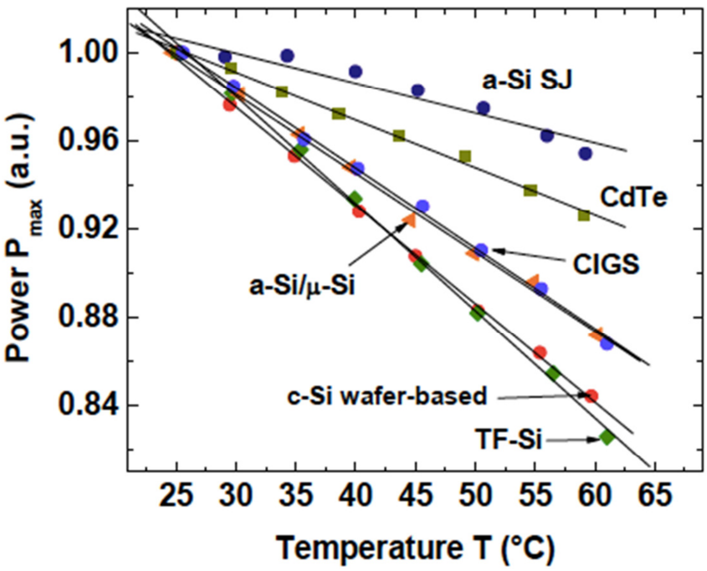

Figure 6: The negative effect of operating cell temperatures on the output power of first- and second-generation PV technologies [36].

[8] In 2015, Series 4-2 First Solar PV modules will be commercially available with higher efficiency, but slightly higher temperature coefficient: -0.34%/°C.

1.2.2. Spectral effects on PV system performance

For first- and second-generation PV technologies, the conversion efficiency of a solar cell device is also dependent on the energy bandgap of the corresponding semiconductor material, and different semiconductors will "see" different portions of the solar spectrum. Figure 7 shows the external quantum efficiency curves for a number of PV technologies, which translates into the device's spectral response. While crystalline silicon and thin-film CIGS PV have a spectral response that spans from 380 nm to around 1180 and 1280 nm respectively (they are "redder" PV devices), thin-film a-Si responds to light in the 360 nm to 790 nm range, and thin-film CdTe will be able to convert into electricity photons in the range from 280 nm to 900 nm. Thin-film a-Si and CdTe are therefore "bluer" solar cell devices than crystalline silicon and CIGS, and will perform better in climates with higher cloud cover levels, which lead to a blue-shifted spectrum. The Standard ASTM G173-03 spectrum was derived based on the spectral distribution of sunlight for a number of high direct normal irradiation level North American locations (DNI levels averaging 2410 kWh/m^2/year and ranging from 2190 to 2740 kWh/m^2/year), where clear skies are predominant, and Aerosol Optical Depths – AOD levels are low. These sites present a much "redder" spectral distribution of sunlight than what is typically found in Brazilian locations, where the presence of different levels of cloud cover lead to a "bluer" spectral distribution. Figure 8 shows the spectral content of sunlight at latitude tilt in Petrolina-PE (latitude 9^{o}23" South), a typical warm and sunny Brazilian Northeast site, in comparison with the Standard ASTM G-173 spectrum. Figure 9 shows, for four Brazilian locations spanning from North to South and West to East, the deviation from the ASTM G-172 spectrum, and it can be seen that the spectral distribution of sunlight at all four Brazilian sites contains more blue photons and less red photons than the Standard ASTM G-173 spectrum. Thus, it can be inferred that, from a spectral content perspective, CdTe PV should be a good performance at these sites.

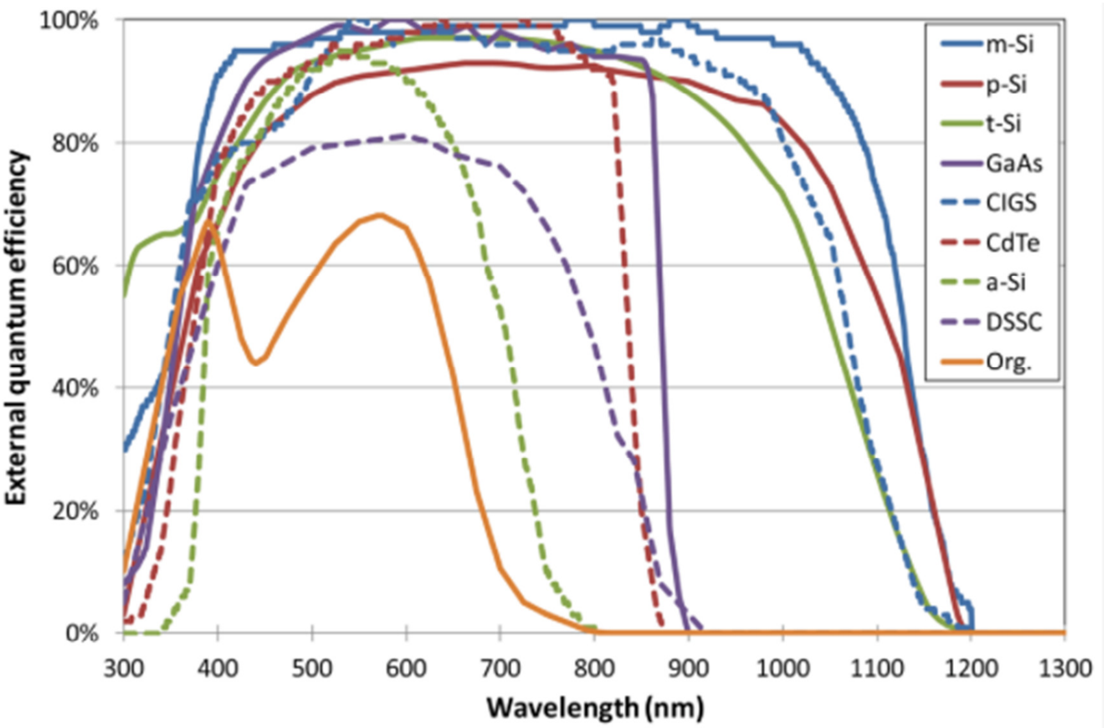

Figure 7: External quantum efficiency curves for a number of solar cell materials. The more shifted to the left (lower wavelengths) a curve is, the better the corresponding material will respond to a blue-shifted spectral content of light [37].

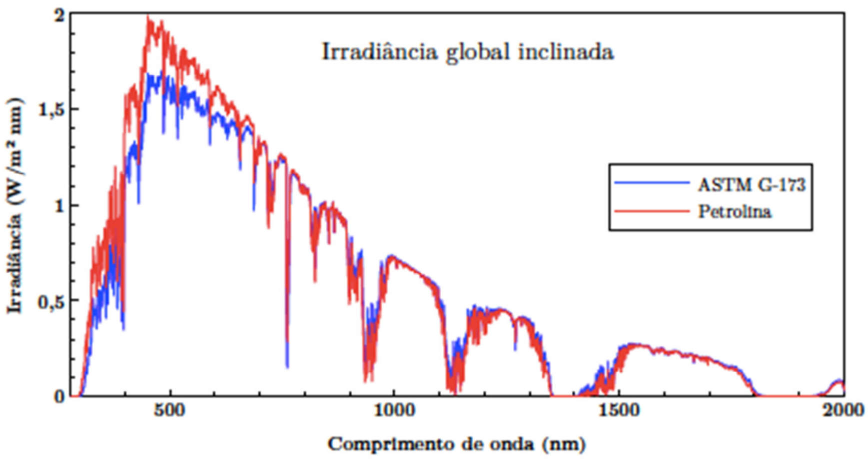

Figure 8: Spectral distribution of sunlight at the Brazilian site Petrolina-PE (latitude = 9o23" South), in comparison with the Standard ASTM G-173 spectrum, showing the higher level of irradiance at lower (bluer) wavelengths at latitude tilted planes [38].

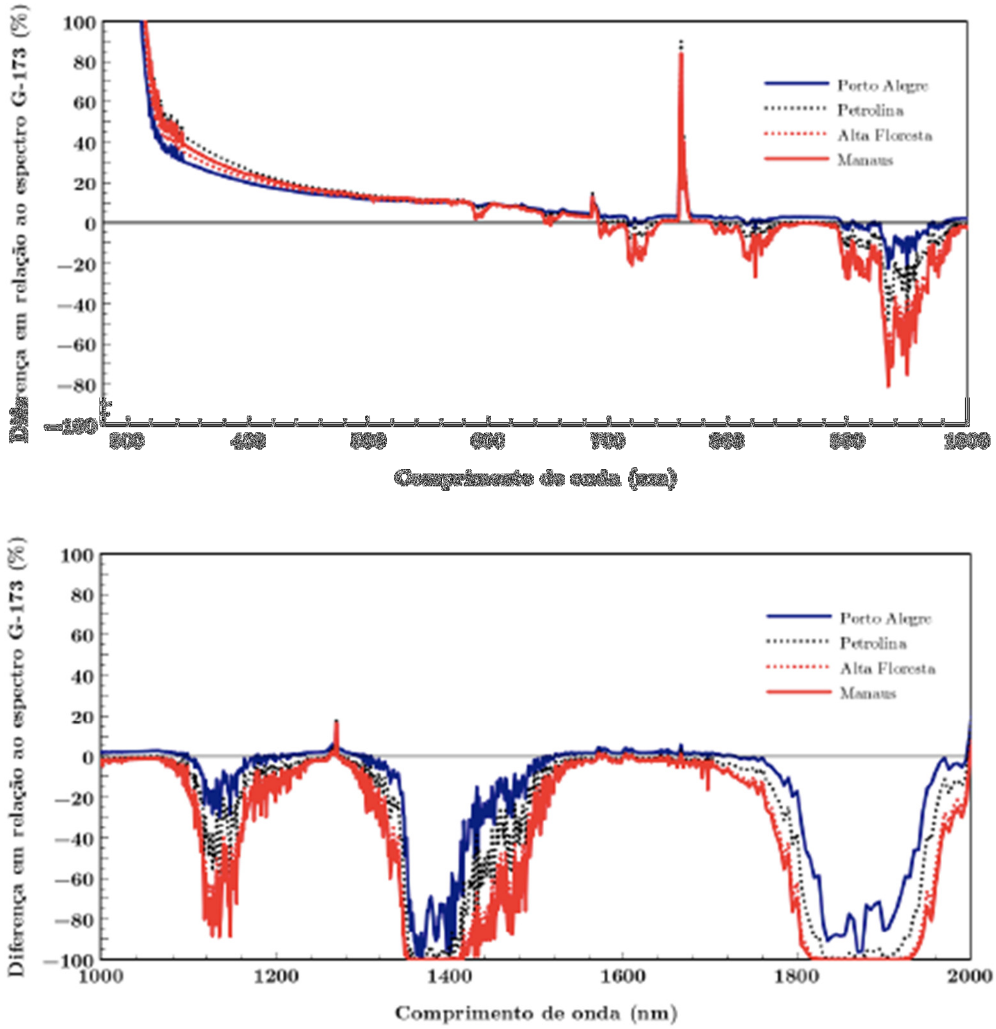

Figure 9: Relative difference between the spectral content of sunlight at four Brazilian sites, and the Standard ASTM G-173 spectrum, showing that the four locations have a spectral distribution that has more blue and less red photons than the standard spectrum [38].

Among the commercially-available PV technologies, thin-film CdTe presents a good combination of high efficiency, low temperature coefficient ($T_{coeff}P_{max}$), and spectral response match with the spectral content of sunlight at Brazilian sites. It is expected that this technology will present a superior performance in terms of kWh generated (= revenue) per installed kWp (= investment) in Brazil.

1.3. First Solar's CdTe thin-film PV technology, efficiency and cost roadmap

First Solar was founded in 1999 after acquiring Solar Cells Inc, and was the first PV manufacturer to produce 1 GWp of solar modules in a single year, and to break the US$ 1/Wp manufacturing cost barrier (US$ 0.63/Wp in 2013[9]). First Solar was also the first PV manufacturer to implement a global PV module recycling program in 2005. The basic First Solar PV product is a 12 kg, frameless, glass-glass 60 cm x 120 cm laminate, where a number (currently 216) of monolithically-integrated CdTe/CdS semiconductor PV cells are sandwiched between a 3.2 mm heat strengthened front glass and a 3.2 mm tempered back glass. On that same 0.72 m^2 surface area, 2004 vintage PV modules were rated at 45Wp (6.25% conversion efficiency), and today PV modules with up to 110Wp (15.28% conversion efficiency) at Standard Test Conditions – STC[10] are currently available (Q1-2015).

On top of developing its own technology and manufacturing of CdTe solar modules, First Solar is also a solar power plant developer and contractor (3+ GWp contracted project pipeline in 2014) and currently operates more than 2 GWp of CdTe power plants, with an average system availability of over 99%[11]. The company is pioneering in the development of advanced grid integration, plant control and forecasting, and energy scheduling capabilities, aiming at integrating utility-scale solar PV into the global energy mix. In an effort to further reduce large-scale PV generation costs, First Solar has recently raised its maximum PV module voltage rating to 1500 V, which results in lower BOS costs. First solar has also concentrated its marketing efforts and strategic positioning on the PV market with a focus on utility-scale, multi-megawatt projects, and has successfully managed to build some of the largest PV projects so far. As Figure 10 shows, with the phasing out of feed-in incentive PV programs worldwide, the PV market is shifting from smaller and distributed residential rooftop PV generators, to more commercial, utility-scale solar power plants, where economies of scale continue to lead to consistent year-on-year cost reductions.

[9] T. de Jong, "Manufacturing Update," First Solar Analyst Meeting, 2014.
[10] STC are the Standard Test Conditions under which all PV modules are nameplate rated. These laboratory conditions include: Irradiance = 1000 W/m2; cell temperature = 25 °C, and spectral content of sunlight equivalent to AM 1.5
[11] T. Kuster, "System Technology Update," First Solar Analyst Meeting, 2013.
G. Antoun, "EPC, O&M and Market Segments," First Solar Analyst Meeting, 2014.

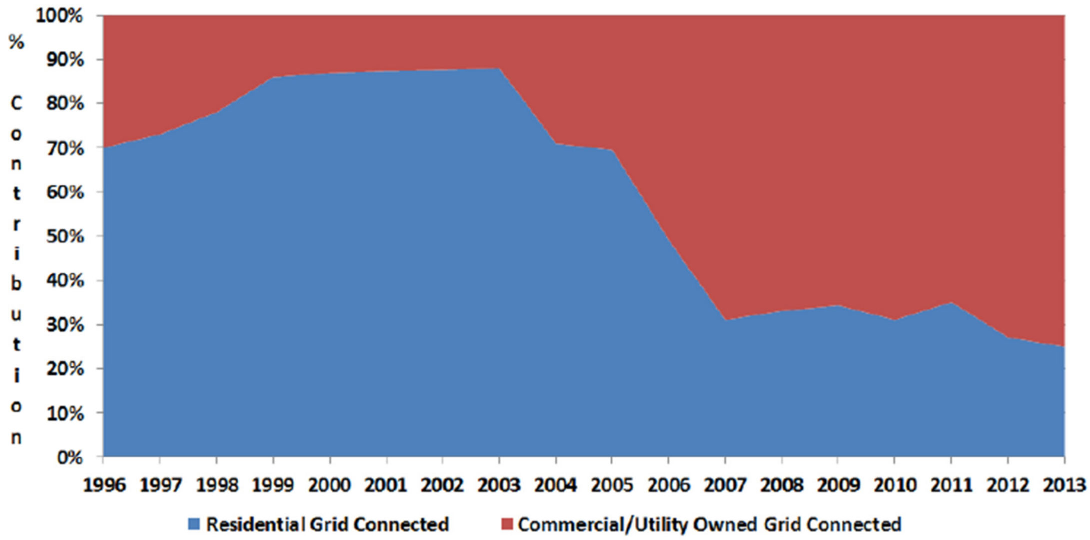

Figure 10: Evolution of the share between small-scale, residential grid-connected and utility-scale, multi-megawatt solar PV installations [39]. Large-scale currently represent more than 2/3 of the world PV market.

CdTe can be produced by a variety of technologies including closed-space sublimation (CSS), vapor transfer deposition (VTD), eletrodeposition, screen printing, plasma vapor deposition or sputtering among others [15,28]. First Solar processes its modules using high-rate vapor transfer deposition (VTD), which is similar to CSS (closed-space sublimation). The key is that the deposition rate of VTD is very high, and First Solar converts glass to module in less than 2.5 hours.

First Solar has owned and operated three CdTe PV module manufacturing and recycling facilities, namely in Perrysburg-OH, USA (PBG); Frankfurt-Oder, Germany (FFO); and Kulim, Malaysia (KLM). Figure 11 shows the total annual PV module production at each site and the total cumulative annual production. With the phasing out of the German feed-in incentive program, the German facility's manufacturing operations were interrupted in 2012, and the FFO plant currently hosts only First Solar's recycling activities. Through efficiency and throughput improvements, First Solar expects to have a combined annual manufacturing capacity of some 3500 MWp by 2018. First Solar dedicates about 25% of the PBG capacity to R&D and spends 4.5% of its revenue on R&D. At the end of 2013 First Solar was running each of the individual manufacturing lines at a Line Run Rate of 79 MWp/year, and at 0.63 US$/Wp manufacturing costs. R&D developments in back contact and anti-reflective coating led to an output of 89 MWp/year at year's end in 2014. Continuing R&D efforts forecast this figure to reach in excess of 130 MWp/year per individual line by the end of 2018, as shown in Figure 12.

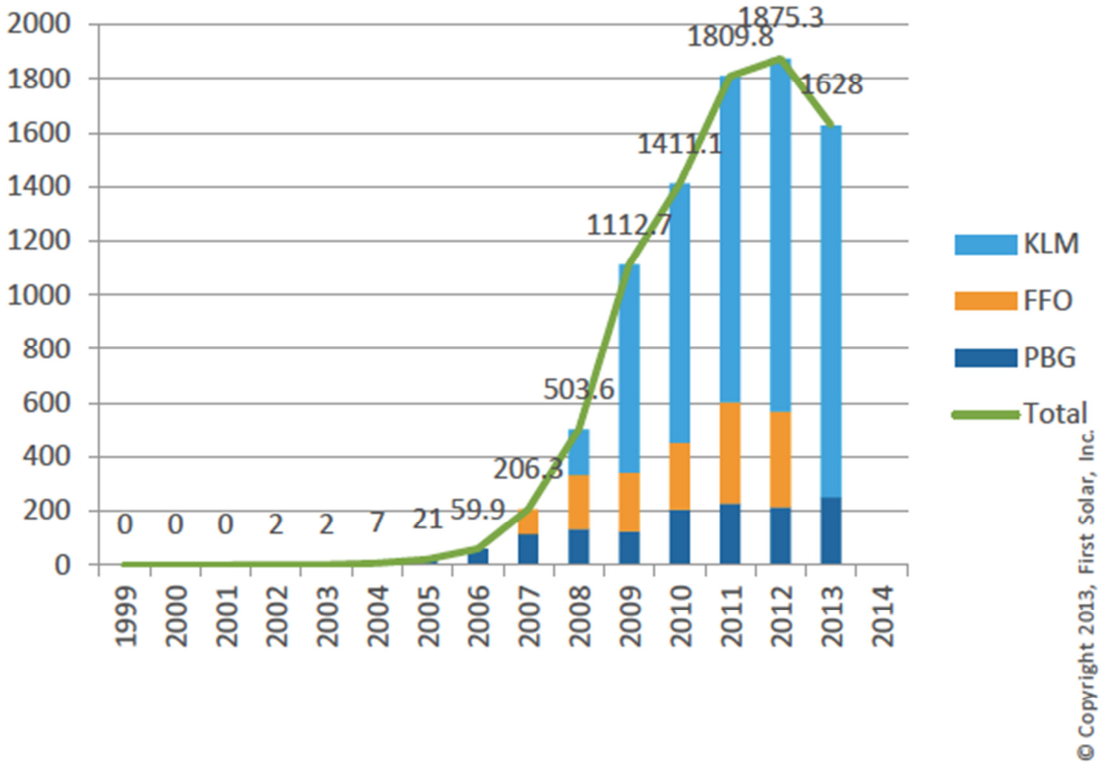

Figure 11: Annual PV module production (in MWpDC/year) for the three CdTe PV module manufacturing and recycling plants that First Solar runs in Perrysburg-OH (USA), Frankfurt-Oder (Germany) and Kulim (Malaysia).

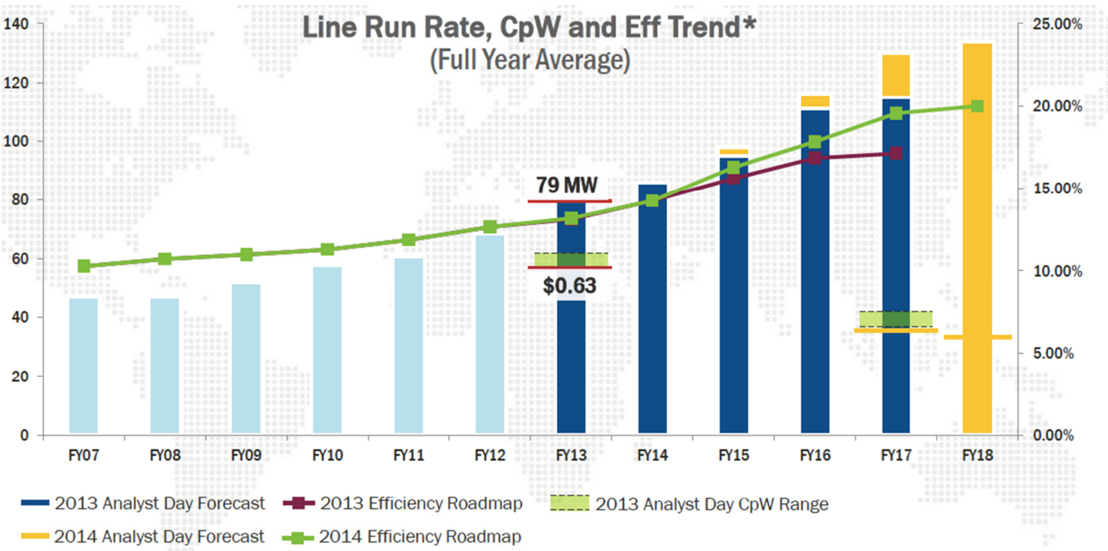

Figure 12: Annual increments in First Solar Line Run Rates, and the reviewed Efficiency Roadmap, with PV module efficiencies of 15% at the end of 2014, 20% in 2017-18.

The efficiency roadmap presented in Figure 13 shows First Solar's thin-film CdTe PV module improvements expected to lead to efficiencies approaching 20% by 2017-18. First Solar's PV module and PV systems cost roadmaps are qualitatively shown in Figure 14, as it is expected that efficiency increases should lead to production cost reductions. In 2017 First Solar expects CdTe PV system costs to drop to below the 1 US$/Wp mark.

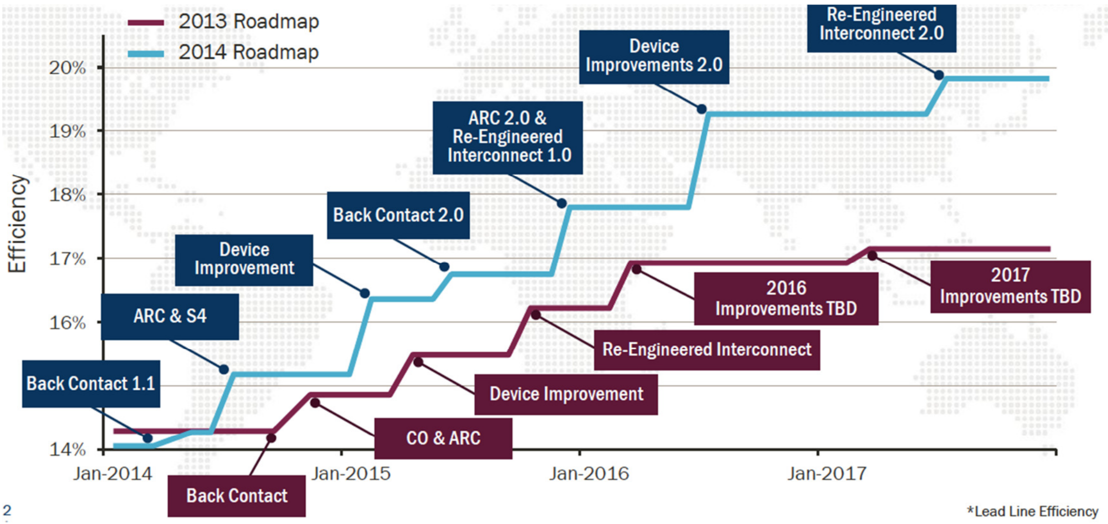

Figure 13: First Solar efficiency roadmap, showing the company's R&D strategies for CdTe PV module efficiency improvements in the period 2014-17.

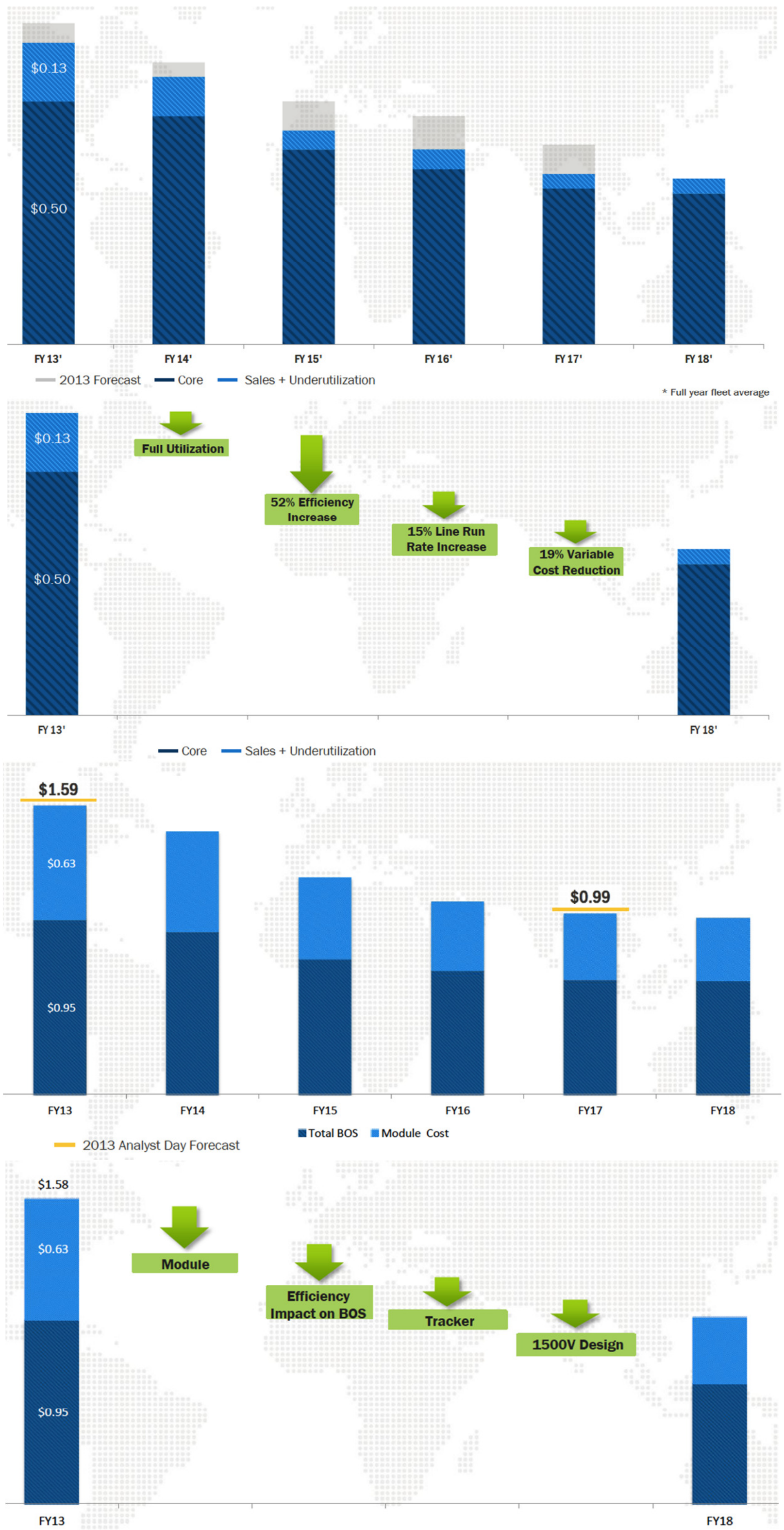

Figure 14: First Solar cost-reduction roadmap, showing the company's strategies for CdTe PV module (first and second charts) and solar power plant (third and fourth charts) cost reductions in the period 2014-18. In 2017 the company expects CdTe PV system costs to drop below the 1 US$/Wp mark.

The manufacturing processes used by First Solar in the production of CdTe PV modules are the same in all First Solar manufacturing plants around the globe, and the company adopted a so-called "Copy Smart" replication philosophy for quickly building new manufacturing facilities and minimize the risk of schedule, cost, environmental, health and safety issues, while guaranteeing product quality and uniformity. First Solar solar modules are identical wherever in the world they are manufactured, and new manufacturing lines operate with the same effectiveness as the base plant in Perrysburg in terms of costs, yields, and consistency. Continuous improvements achieved in any of the manufacturing plants can be realized and transferred quickly and globally after the concept has been proven at one location.

The next section presents a literature review on environmental, health and safety aspects of CdTe PV module production, transportation, utilization, decommissioning and recycling, showing the impacts and benefits of First Solar's solar generation technology for large-scale deployment in Brazil. The last section of this report presents issues related to the performance of PV in warm climates.

2. Literature review on Cadmium Telluride (CdTe)

2.1. Safety – Do CdTe PV systems represent an environmental, health, or safety risk under normal operating conditions and foreseeable accidents, up to the end of the life of the product, including recycling?

Concerns have been raised about CdTe PV modules related to the heavy metal Cd, and the possibility of its release, either during module manufacture, transportation, deployment, decommissioning or recycling [15]. The lifecycle of CdTe includes: (i) Cd and Te mining as a by-product of the mining of Zn, Pb and Cu ores, and the smelting/refining of Zn, Pb and Cu; (ii) Cd and Te purification; (iii) CdTe production; (iv) manufacture of CdTe PV modules; (v) transportation, installation and commissioning, and deployment of CdTe PV modules in solar power plants; and (vi) decommissioning, transportation and recycling of CdTe PV modules at end-of-life.

Do CdTe PV systems represent an environmental, health or safety (EHS) risk under normal operating conditions and foreseeable accidents, up to the end of their lifetime? This section aims at presenting information to assist in answering this question, based on independent and bona fide data obtained from a representative sample of publicly-available reports and studies. While no direct or first-hand investigations were carried out on any of the aspects reported in this section, care was taken to present only information regarded as trustworthy. Some of the information presented on aspects of CdTe industrial production processes was obtained directly from First Solar, and a site visit to First Solar's manufacturing plant in Perrysburg-OH, USA was carried out in September 2014. This manufacturing plant visit included communications with First Solar staff at the site and covered CdTe module production and recycling processes, PV module quality and reliability test laboratory, in-house wastewater treatment facility, and debriefing on First Solar's EHS efforts. First Solar ensures authenticity and validity of all data provided for this report.

2.1.1. CdTe chemistry and toxicology

The compound CdTe has different qualities than the two elements, cadmium and tellurium, taken separately. Toxicity studies show that CdTe is less toxic than elemental Cd, which is a lung carcinogen, with long-term detrimental effects also on liver, kidney and bones due to calcium loss, but not as much is known about the compound CdTe [9,10,16,26]. CdTe has low acute inhalation, oral, and aquatic toxicity, and is negative in the Ames mutagenicity test[12]. Based on notification of these results to the European Chemicals Agency (ECHA), CdTe is no longer classified as harmful if ingested nor harmful in contact with skin, and the toxicity classification to aquatic life has been reduced [21]. Once properly and securely captured and encapsulated, CdTe used in manufacturing processes may be rendered harmless. Current CdTe modules pass the US EPA's Toxicity Characteristic Leaching Procedure (TCLP) test, designed to assess the potential for long-term leaching of products disposed in landfills [16]. Due to the strong ionicity of the CdTe and CdS compounds (72%) [40], the energy of any photon contained in sunlight is lower than the energy (> 5 eV) required to break the chemical bonds in CdTe or CdS. The strong bonding energies lead to an extremely high chemical and thermal stability, reducing the risk of degradation in performance or any liberation of Cd to a very low level, with no degradation intrinsic to the material to be expected [15].

Toxicological studies reviewed by Kaczmar on the toxicity of CdTe PV [9] were recently carried out in order to register CdTe PV under REACH in the European Union, and are briefly presented in Figure 15.

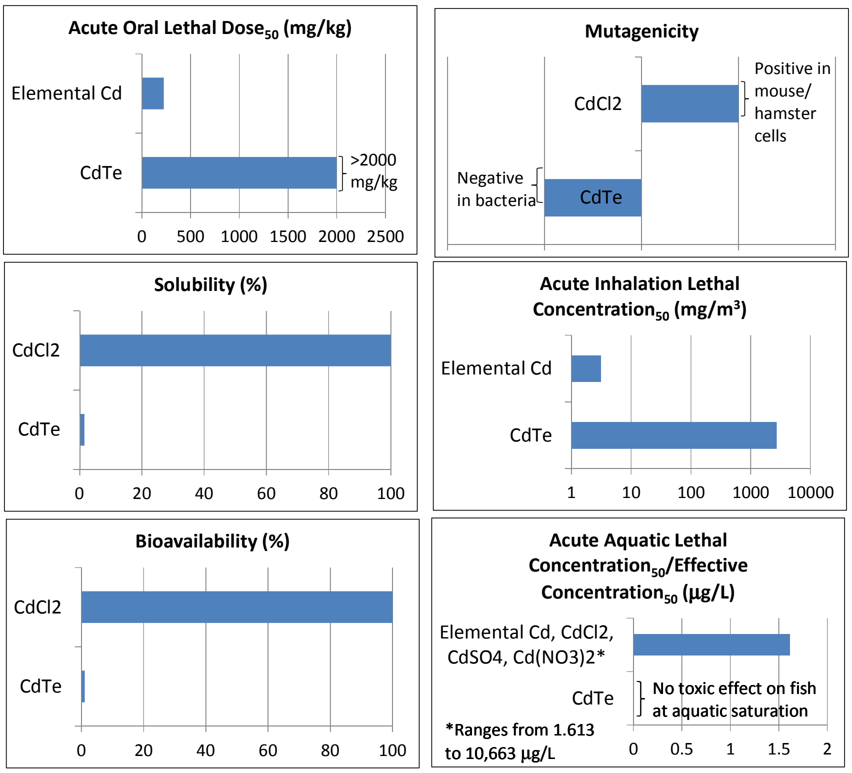

Figure 15: Toxicity, solubility and bioavailability of CdTe in comparison with other Cd compounds [9].

[12] The Ames test is a biological assay to assess the mutagenic potential of chemical compounds (http://www.princeton.edu/~achaney/tmve/wiki100k/docs/Ames_test.html).

In the processing of CdTe PV modules, First Solar uses CdTe and CdS, which are the active semiconductors that end up encapsulated between the two 3.2 mm thick glass panes, and also $CdCl_2$, which is sprayed on the CdTe layer to promote grain enlargement and improve photovoltaic conversion efficiency. CdTe and CdS are insoluble compounds, while $CdCl_2$ has a solubility of 1400 g/L [26]. After the grain enlargement process, however, $CdCl_2$ is washed off and is not a component of the finished PV module. Wastewater is treated on-site and tested to confirm compliance to permit limits before discharging (see Section 2.4).

2.1.2. Raw material sourcing and availability

Cadmium is a soft, bluish-white metallic element, one of the naturally occurring components in the earth's crust and waters, and present everywhere in our environment. It was first discovered in Germany in 1817 as a by-product of the Zn refining process. Its name is derived from the Latin word *cadmia* and the Greek word *kadmeia* that are ancient names for calamine or zinc oxide[13].

Tellurium is a brittle, mildly toxic, rare, silver-white metalloid, which is occasionally found in native form, as elemental crystals. Tellurium is far more common in the universe as a whole than it is on Earth. Its extreme rarity in the Earth's crust, comparable to that of Pt, is partly due to its high atomic number, but also due to its formation of a volatile hydride, which caused the element to be lost to space as a gas during the hot nebular formation of the planet. Tellurium was discovered in the Austro-Hungarian Empire in 1782 in a mineral containing Te and Au, and was named after the Latin word for "earth", *tellus*. AuTe minerals are the most notable natural Au compounds. However, they are not a commercially significant source of Te itself, which is normally extracted as a by-product of Cu and Pb production[14].

In this study, environmental, health and safety issues related to raw material sourcing in the production of CdTe PV solar modules are restricted to the active CdTe compound semiconductor itself, since from an EHS's perspective this is the most Cd-abundant material in this thin-film PV module production process, and also because CdS (active semiconductor material) and $CdCl_2$ (used for in-process grain enlargement, and then washed off) each contribute to only about 4% of the mass of CdTe used in module production. The active PV semiconductor device is comprised of both CdTe and CdS compounds, with thicknesses of up to 3 µm and 0.2 µm respectively. With the current First Solar CdTe PV module efficiencies of 15%, less than 54g of Cd, are used per

[13] http://www.cadmium.org
[14] http://www.mindat.org/min-3906.html

kWp (less than 5.8 g of Cd per individual 0.72 m^2 module, which is less than the Cd content of 2 x AA size rechargeable NiCd batteries [41].

CdTe is manufactured from pure Cd and Te, both of which are byproducts of smelting prime metals (e.g. Cu, Zn, Pb, and Au). Cadmium is generated as a byproduct of smelting Zn ores (~80%), Pb ores (~20%), and, to lesser degree, of Cu ores. Tellurium is a byproduct of Cu refining. Cadmium is used primarily in Ni–Cd batteries. Its previous uses in anticorrosive plating, pigments, and stabilizers were drastically curtailed. Cadmium is also used in the control rods of nuclear reactors. Tellurium is a rare metal used in manufacturing photosensitive materials and catalysts. Cadmium minerals are not found alone in commercial deposits. The major Cd-bearing mineral is sphalerite (ZnS), present in both Zn and Pb ores. Tellurium minerals are not found alone in commercial deposits. Tellurium is a rare metal that can be extracted as byproduct of processing Cu, Pb, Au, and Bi ores, and most of the tellurium is recovered from the slimes formed during the electrolytic refining of Cu [41]. CdTe is produced from Cd and Te powder via proprietary methods. CdTe is produced in small amounts for detectors and photovoltaics. Production is limited and the volumes produced are not published. Reportedly, 100% of the feedstock is used and there are no quantifiable emissions during CdTe formation. The electrolytic purification does not produce any emissions and all waste is recycled. The melting and atomization steps necessary to form the CdTe powder emit about 2% of the feedstock which are captured by High Efficiency Particulate Air HEPA filters [41].

The current and projected annual growth of the solar PV market, and the vision of solar becoming a relevant component of the electricity generation market will involve a few terawatts of PV to be installed worldwide before 2050. In this context, raw materials availability for CdTe PV module production might become an issue, and Te availability is the most critical aspect for this technology development at the gigawatt level. Current Te use in 3µm thick, 15% efficient CdTe solar cell devices is around 67 MT/GWp, with prospects of reducing this amount considerably by both efficiency increases and cell thickness reductions [35,42,43]. In 2010, CdTe PV module production accounted for about 26% of Te worldwide consumption [42], and as a by-product of Cu smelting, Te commercial availability is reportedly constrained to 16–24 GWp/year in 2020, 44–106 GWp/year in 2050, and 60–161 GWp/year in 2075 [43]. The projections shown in the literature have not counted on more Te from new BiTe ores, undersea ridges, or greater refining of non-Cu ores [35].

2.1.3. Manufacturing

As previously mentioned, First Solar owns CdTe PV module manufacturing capacity in the USA (PBG) and Malaysia (KLM) and complete, monolithically integrated PV modules are produced starting from glass and ending in a finished and ready-to-use glass-glass, unframed PV laminate. Figure 16 shows a simplified schematic representation of this process flow, in which semiconductor deposition, PV cell definition, and final assembly and testing of the finished PV module are all carried out at the same manufacturing facility.

Figure 16: Conceptual and simplified flow of First Solar CdTe manufacturing process, from glass to finished PV module, in which all process steps are carried out at the same manufacturing plant.

For over two decades, originally as Solar Cells Inc., and since 1999 as First Solar Inc., the company has been engaged in the production of CdTe PV modules. During this period, much data has been accumulated on all facets of worker and environmental exposures to the Cd compounds used to manufacture this product. A large number of routine medical monitoring tests have been done on First Solar workers to track any biological responses to occupational Cd exposures. A similarly large number of industrial hygiene air samples have been collected to determine Cd exposure during specific manufacturing processes and maintenance procedures. Further, air emissions, emissions as industrial wastewater and solid wastes have been either measured or calculated using engineering estimates such as mass balance. The Cd management effort is complimented by a comprehensive safety management system. The heart of this system is a formal hazard recognition system designed to identify and proactively control workplace hazards [44].

First Solar devotes great care to the safety, industrial hygiene, and occupational health of employees, and carries out regular medical monitoring of staff involved in certain manufacturing activities (e.g. a comprehensive physical exam upon joining the company, and periodic blood and urine analysis). First Solar also has safety teams in place in each factory. First Solar has established an occupational, health and safety - OH&S management system (OHSAS 18001) to eliminate or minimize risk to employees and other parties who may be exposed to OH&S risks associated with the company's manufacturing activities, and has reduced the recordable incident rate - RIR at its factories from 2.6 in 2008 to 0.48 in 2014. Furthermore, in terms of Cd air contamination, the company has established a globally comparable air sampling strategy on a quarterly basis, and whenever there is a new plant or new equipment set up, potential exposure areas are barricaded and respirators are required within barricaded areas until qualification sampling is done and proven exposure controls are operating properly. Figure 17 shows the average Cd levels at the Malaysia KLM factory, which are well below the First Solar action limit of 1 µg/m^3. During certain maintenance activities Cd levels may exceed the action limit. During these activities, workers wear personal protective equipment such as HEPA respirators and impermeable coveralls.

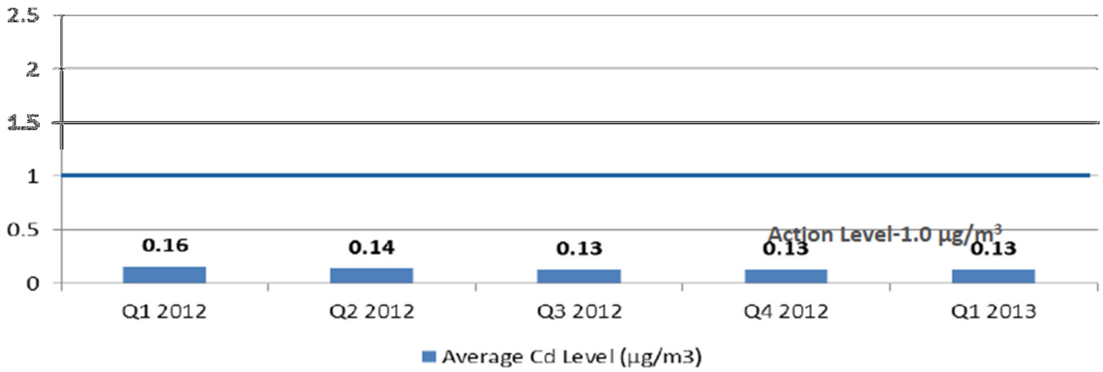

Figure 17: Cd levels routinely measured at the Malaysia KLM First Solar factory, which are well below the action limit of 1 µg/m^3.

Figure 18 shows sampling results of personal exposure to Cd at the various stages of manufacturing process at First Solar CdTe PV module production plants.

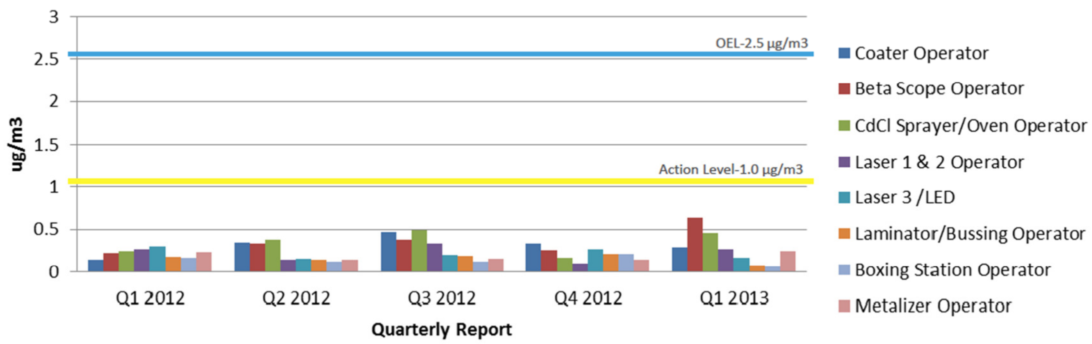

Figure 18: Personal exposure to Cd at First Solar manufacturing plants for the various stages of CdTe PV module production.

First Solar has accumulated several years of biomonitoring and industrial hygiene data, which are well below regulatory limits, and which validate the company's excellent control of Cd exposure. Figure 19 shows the biomonitoring results of First Solar's Perrysburg (top) and Malaysia (bottom) manufacturing site, where the mean blood and urine levels of employees are well below the Occupational Safety and Health Administration (OSHA) occupational health exposure limits.

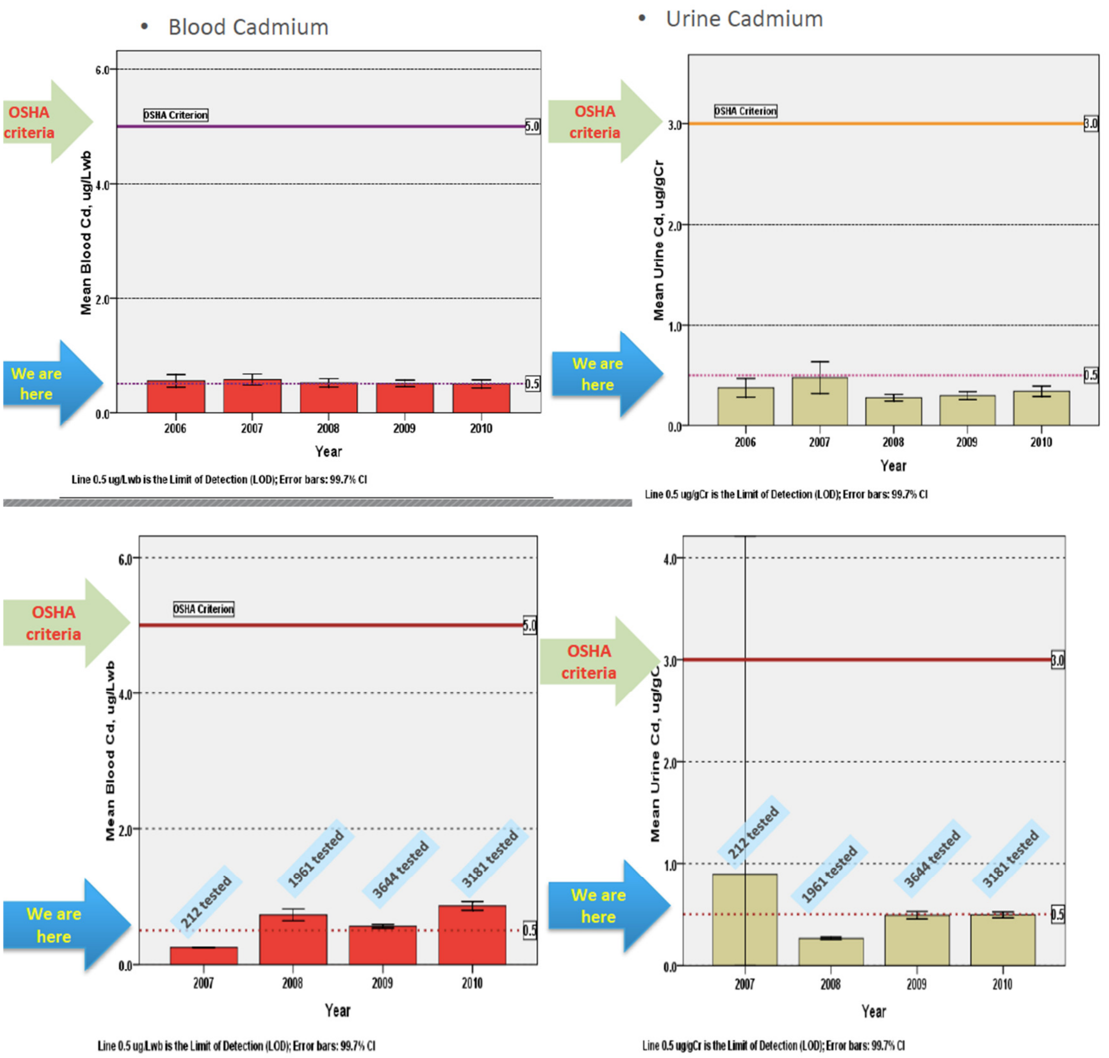

Figure 19: Biomonitoring results of First Solar's CdTe PV module manufacturing plant employees at the Perrysburg (top) and Malaysia (bottom) site.

Figure 20 shows a comparison between First Solar Malaysia (KLM) CdTe PV manufacturing plant employees pre-employment and employment annual Cd content in blood (top) and urine (bottom) for the year 2010 divided by smoking habit. A total of 3181 employees were tested (1253 pre-employment, and 2458 employed). There is no statistically significant difference between the Cd content of pre-employment and employment, but a distinct difference can be seen between the blood Cd content of smokers and non-smokers.

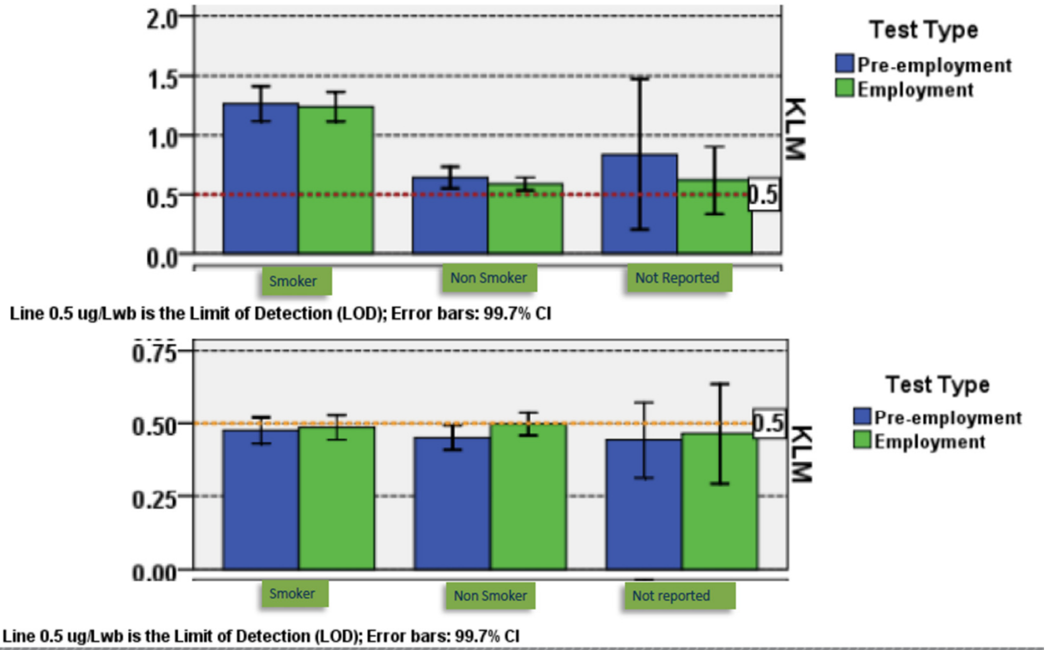

Figure 20: Evaluation of First Solar Malaysia (KLM) CdTe PV manufacturing plant employees' pre-employment and employment annual Cd content in blood (top) and urine (bottom) for the year 2010 divided by smoking habit. A total of 3181 employees were tested (1253 pre-employment, and 2458 employed).

First Solar has more recently started to consider the possibility of transferring part of the CdTe PV module manufacturing steps to other countries, in order to satisfy some local content requirements in new markets like Brazil. The concept of a so-called split line has been proposed by First Solar, and is schematically shown in Figure 21. It is expected that like in the current manufacturing plants, all new First Solar facilities will observe the same stringent EHS criteria.

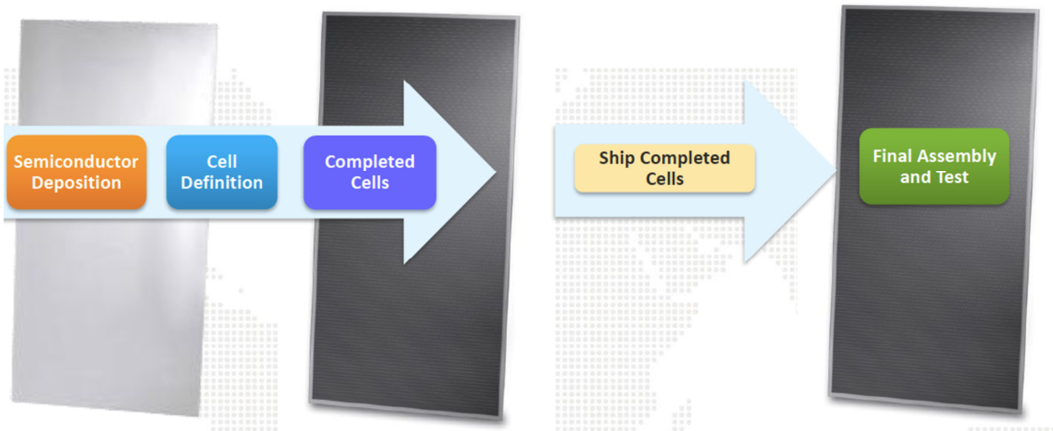

Figure 21: Conceptual and simplified flow of First Solar CdTe split line manufacturing process, from glass to finished PV module, in which some of the initial process steps are carried out at the base plant (PBG or KLM), and bundled single glass panes with completed cells are shipped elsewhere for final assembly and test at another manufacturing plant.

From an EHS standpoint, the manufacture of CdTe PV modules at First Solar is carried out in a controlled and responsible way. The processes from purchase of raw materials to manufacture of modules are all carried out in a closed workshop. Generated atmospheric pollutants generally enter the ventilation system of the workshop equipped with highly efficient HEPA (High Efficiency Particulate Air) filters. The efficiency of HEPA filters in collecting particulates of mean diameter of 0.3µm is 99.97%. Cleaning wastewater from all workshop sections flow to the in-house water treatment plant for centralized treatment. In this way, wastewater and air emissions generated at the site are effectively controlled. Wastewater and water use will be addressed in section 2.4.

2.1.4. Product use

It has been claimed that generating electricity with CdTe thin-film PV systems is an effective way of reducing the Cd content released into the environment (see section 2.2) [11,45]. This rationale is based on two main facts:

(i) Replacing coal-fired electricity generation with electricity generated with CdTe PV systems results in less Cd released to the environment, since coal contains Cd (140 g of Cd released for every GWh of electricity produced in the USA [46]), which is unavoidably released into the environment in coal-fired power plants. In CdTe PV systems, on the other hand, most of the Cd involved is trapped inside the glass-glass laminate. At the end of their useful life or when they are accidentally broken, CdTe PV modules can be disposed of in landfills, since they pass the US

Federal Toxicity Characteristic Leaching Procedure [15] (TCLP leaching criteria for non-hazardous waste [12]; and

(ii) Being a by-product of Zn mining and refining, and because Zn is produced in large quantities, substantial quantities of Cd are generated as an unavoidable by-product, no matter how much Cd is used in PV. This Cd can be either put to beneficial uses or discharged into the environment. When the market does not absorb the Cd generated by metal smelters and refiners, it is cemented and buried, stored for future use, or disposed of in landfills as waste, and arguably, encapsulating Cd as CdTe in PV modules presents a safer use than its current uses and is much preferred to disposing of it [11].

A solar PV module can suffer a breakage at any stage of its working life since transportation, installation, operation, maintenance operations and decommissioning all involve handling or exposure to other conditions that can result in surface damage (e.g. hailstorm events in certain areas). Measured module breakage rates are very low in First Solar's experience of over 2,000 MWp of CdTe PV plants operating in the USA, averaging 0.04%/year [47]. The CdTe compound will remain stable as a solid compound under normal operation conditions. In case of PV module breakage, chemical degradation is unlikely due to the low vapor pressure and low solubility of this compound and due to product design. In First Solar PV modules, CdTe is laminated between two sheets of glass and an industrial polymeric adhesive, which will prevent delamination if a module cracks. Even in a worst-case breakage scenario, potential impacts to soil, groundwater, and air from broken modules are within human health screening levels and background levels [47].

Fire is a common concern in the product use phase, and experimental analysis indicates that CdTe modules do not pose a significant risk during fires. Under the high temperatures of a building fire (800 to 1100˚C), module glass fuses together with Cd diffusing into glass, limiting release [48]. Potential impacts to air quality from CdTe PV fires have been found to be below human health screening levels [49].

2.1.5. Product end-of-life disposal and recycling

The most ideal way of disposing of CdTe PV modules at their end-of-life, as well as of broken/cracked modules in the field, or even for off-spec modules or modules damaged during the manufacturing process is recycling, and First

[15] TCLP is a U.S. hazardous waste characterization test. Under Brazilian law, waste containing Pb or Cd is listed as hazardous waste regardless of the volume of the chemical it contains (Brazilian Association of Technical Standards - ABNT by means of the normative NBR 10004:2004). Since Pb and/or Cd compounds are commonly used in commercial PV modules [9], these modules are likely to be characterized as hazardous waste at end-of-life if disposed of in Brazil. However, note that they will not be classified as waste or hazardous waste under Brazilian law to the extent that they are not finally disposed of in Brazil (e.g., transported outside of Brazil for recycling).

Solar has established a comprehensive recycling process in 2005, with recycling facilities operational in all manufacturing plants and an annual recycling capacity of around 26,000 MT. Figure 22 shows First Solar's PV module recycling process flow, consisting of a shredder; hammermill; reactor column, where PV module fragments are mixed with an acidic solution to separate the semiconductor materials from the solid glass and the encapsulant; and metal precipitation vessel. After precipitation and filter pressing, Cd- and Te-rich cakes are sent to third parties for Cd and Te refining, with up to 95% of the metals recovered. The shredded glass is sent to a third party, with 90% recovered, where it is used to produce new glass products. The encapsulant is disposed of according to local waste disposal standards or incinerated for energy recovery.

Releases to the environment could potentially occur after decommissioning only if such modules are disposed of in unlined landfills without leachate collection and treatment systems and assuming that the cadmium compounds leach out. However, cadmium telluride is encapsulated between two sheets of glass and is unlikely to leach to the environment under normal conditions [26,50].

Starting in 2014, the European Union regulatory framework on Waste Electrical and Electronic Equipment (EU WEEE) mandates recycling for all PV module technologies, with collection and recovery targets, as well as minimum treatment requirements. Recycling of PV modules is a growing and potentially profitable business, and with the inclusion of PV in the EU WEEE Directive, First Solar projects this business to yield around 17.5 billion Euros industry-wide by 2050, as recycling costs decline with volumes, as shown in Figure 23.

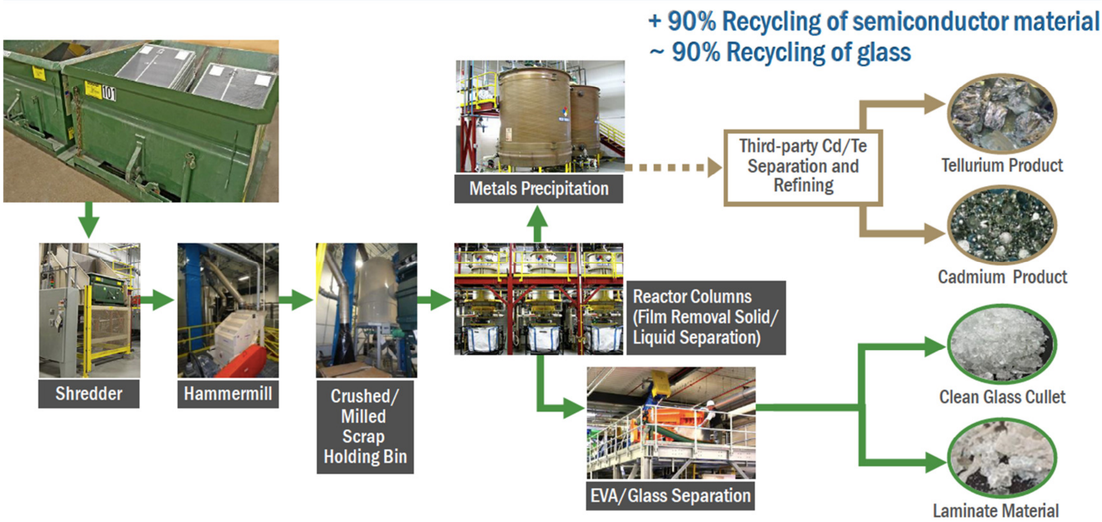

Figure 22: Process flow of First Solar's CdTe PV module recycling process. After metal precipitation carried out in-house, Cd and Te separation and refining are done by third parties.

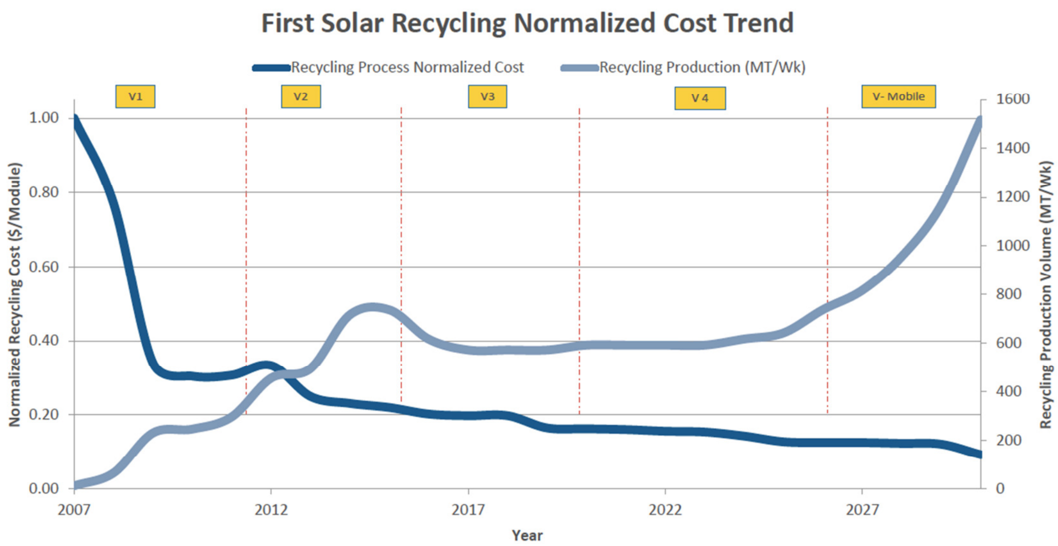

Figure 23: Evolution of the normalized recycling costs (US$/module) for First Solar CdTe PV module recycling process. Version V2 is currently in place, with V3 expected to come in line shortly.

2.2. Carbon footprint, Energy Pay Back Time (EPBT), and heavy metal emissions

Thin-film CdTe PV power plants will not increase heavy metal pollution to the environment during the normal installation and operation phases, but can bring Cd pollution to the atmosphere to some extent in the early phases including mining, ore grinding, roasting, smelting and refining. Relevant studies and First Solar data show that Cd pollution to the atmospheric environment can potentially be generated during solar PV module manufacturing, especially in the steps of thin-film production and crystal growth, and laser scribing. Cadmium-containing exhaust from the processes is generally disposed of in a compliant manner after dust collection, using 99.97% efficient High Efficiency Particulate Air (HEPA) filters, as shown in Figure 24. The remaining residual cadmium-containing pollutants in exhaust after dust collection are recirculated within the manufacturing facility with average factory-wide Cd concentrations in indoor air (<0.2 μg/m^3) that are well below occupational exposure limits (5 μg/m^3).

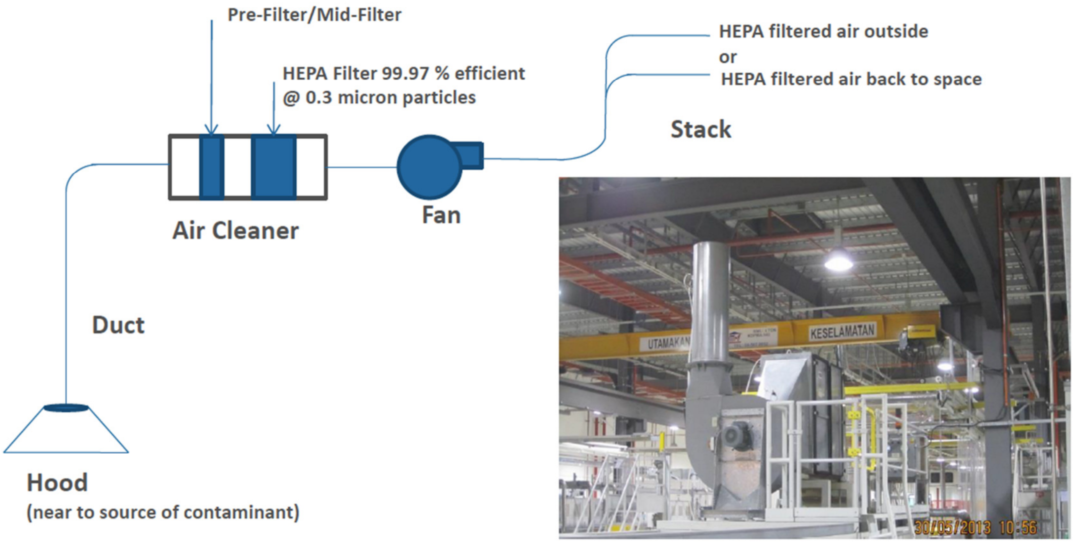

Figure 24: First Solar's CdTe PV module manufacturing plant Local Exhaust Ventilation (LEV) system. The photo shows the High Efficiency Particulate Air (HEPA) filter's exhaust air being recirculated back to the manufacturing floor space.

Han et al. [51] have reviewed the effects of environmental Cd on human health, and have concluded that it is important to (i) continue to conduct follow-up studies and analyze trends on health hazards, in order to evaluate Cd exposure and the severity of health damage related; (ii) collect and screen the information of population disease and death closely related to Cd exposure, and study the link and dose-response relationship between kidney damage and Cd exposure; (iii) establish human health hazard monitoring and early warning network of Cd exposure in the framework of environmental public health monitoring; (iv) implement prevention and intervention research on population health hazards of environmental Cd exposure to reduce contamination risks. Note that potential emissions from the mining and refining of Zn and Pb occur regardless of the use of their byproducts in PV [41].

In Figure 25, Fthenakis et al. [45] compared the lifecycle atmospheric Cd emissions of PV systems to other sources of electricity generation, showing the generating electricity with CdTe PV systems will release more than ten times less Cd into the environment, than producing electrical power on a coal-fired power plant.

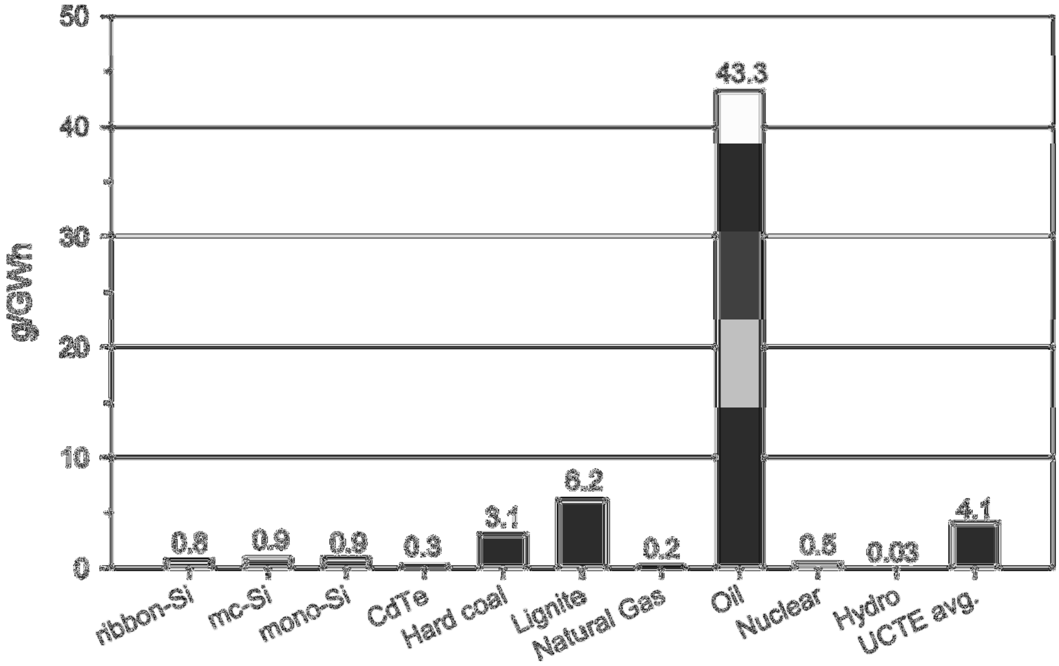

Figure 25: Lifecycle atmospheric Cd emissions for ground-mounted PV systems from electricity and fuel consumption for a Southern European average insolation of 1,700 kWh/m2/year, performance ratio of 0.8, and lifetime of 30 years [45].

The Energy Payback Times (EPBT) of the commercially-available solar PV technologies are shown in Figure 26. For all PV technologies, the energy involved in producing solar modules is paid back many times over the expected lifetime of a PV solar generator. Due to its low energy requirements, the manufacturing of CdTe PV modules presents the lowest EPBT in the photovoltaic industry.

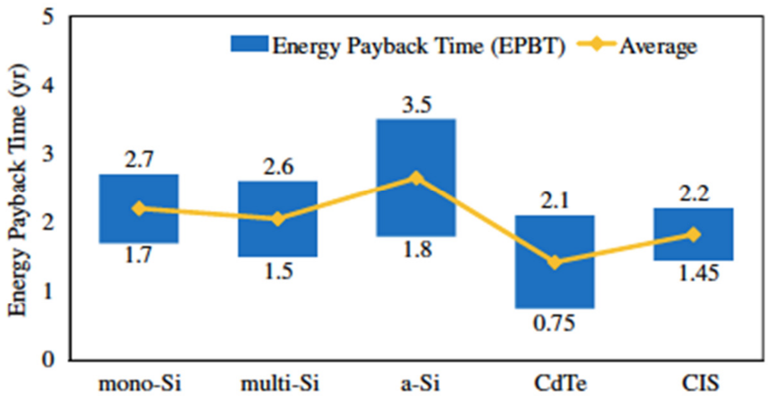

Figure 26: Energy Payback Times (in years) for commercially-available solar PV technologies [52].

A SimaPro LCA analysis of the carbon footprint was carried out by First Solar for solar farms using 15% First Solar CdTe PV modules operating in Brazil[16] for different combinations of optimum annual electricity yield (2,000 and 2,300 kWh/kWp/year), 80% Performance Ratio, annual output degradation (0.5 and 0.7 %/year), and power plant lifetime (25 and 30 years). CO_2 footprint values for First Solar's CdTe PV systems ranged from 11.9 to 16.6 g CO_2-eq/kWh for PV modules produced using the USA energy mix, and from 9.6 to 13.4 g CO_2-eq/kWh for PV modules produced using the Brazilian energy mix. Energy payback times for First Solar CdTe PV plants operating in Brazil varied from 0.82 to 0.94 years at the sunniest sites, to 1.22 years under the worst possible solar irradiation conditions in the country. The CO_2 footprint values for crystalline silicon PV, on the other hand, are considerably higher, ranging from 30 to 60 g CO_2-eq/kWh for multi- and monocrystalline silicon respectively, and the EPBT range from 1.82 to 3.07 years respectively.

2.3. Land use and biodiversity

Renewable energy sources are typically dispersed and difficult to collect, thus requiring substantial land resources in comparison to conventional energy sources. Fthenakis and Kim [53] have presented the normalized land requirements during the life cycles of conventional and renewable energy options, covering coal, natural gas, nuclear, hydroelectric, PV, wind, and biomass. They have compared the land transformation and occupation matrices within a lifecycle framework across those fuel cycles. Although the estimates vary with regional and technological conditions, the PV cycle requires the least amount of land among renewable-energy options, while the biomass cycle requires the largest amount. Moreover, they have determined that, in most cases, ground-mount PV systems in areas of high insolation transform less land than the coal-fuel cycle coupled with surface mining. In terms of land occupation, the biomass fuel cycle requires the greatest amount, followed by the nuclear fuel cycle.

Solar PV is an area-intensive energy generation technology, and at 15% conversion efficiency PV modules installed side by side on a horizontal surface will lead to a nominal power of 150 W/m^2 (6,667 m^2/MWp). However, land is required in addition to that accommodating the PV module array, for access, maintenance and also to avoid shading. At the low-latitude sites in Brazil where most of the PV solar farms will be installed, PV modules will be mounted on fixed metal racks typically tilted at 10^o facing true North (or on single-axis tracking structures). For fixed PV arrays, module spacing and distance between module rows (a typical pitch is 2.5 m) will lead to area requirements of about 14,000 m^2/MWp.

[16] Assuming the Brazilian current electricity generation mix and a grid efficiency of 64%.

The largest potential impact of utility-scale PV solar plants to wildlife and habitat is due to land occupation by the solar power plant itself. If the solar power plant is enclosed by a fence, hiding spots, preying strategy, and food availability will all be affected. Power plants can also prevent vegetation growth, and a significant alteration to the vegetation might occur. The PV arrays themselves will cast shadows and might change the microclimate, causing effects on vegetation that have not been previously studied. The installation of a PV power plant might involve suppression of vegetation in the development area, with withdrawal of soil vegetative coverage favoring erosive processes. In most of the regions where solar PV plants are likely to be installed in Brazil, the land is not particularly adequate for agricultural activities, and it is not envisaged that PV power plants will compete with agricultural or livestock production, or lead to the removal of forests in this 8.5 million square km country. However, the impact to wildlife will be tightly correlated to the biodiversity of the land on which the solar power plant is built. Sunlight and water availability can significantly alter the biodiversity in any of these biomes. Consequently, a customized study of the wildlife and ecosystem surrounding each power plant is recommended as a best practice. In addition to potential impacts on biodiversity, solar projects can have potential benefits for biodiversity due to their static use of land [26]. Although construction projects always involve disturbance of existing flora and fauna, with solar parks there is a chance to improve the quality of habitats for various plant and animal species and even to create new habitats [54]. Table 2 summarizes ecological impacts of solar power plants displacing power generated by the traditional U.S. technologies.

Table 2: Impacts to human health and well-being (top) and wildlife and habitat (bottom) of solar electricity generation relative to traditional USA power generation [55].

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Emissions of mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Emissions of cadmium	Reduces emissions	Beneficial	High	Solar emits ~150× less cadmium
Emissions of other toxics	Reduces emissions	Beneficial	Moderate	Solar emits much less
Emissions of particulates	Reduces emissions	Beneficial	High	Solar emits much less
Other impacts				
Noise	Reduces noise	Beneficial	Low	Less mining noise; less train noise
Recreational resources	Reduces pollution	Beneficial	Moderate	Cleaner air; cleaner fishing
Visual aesthetics	Similar to fossils	Neutral	Moderate	Solar farms vs. open pit mines
Climate change[a]	Reduces change	Beneficial	High	Solar emits ~25× less g h g
Land occupation	Similar to fossils	Neutral	Moderate	See Section 4.1

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Acid rain: SO NOx	Reduces emissions	Beneficial	Moderate	Solar power emits ~25× less
Nitrogen, eutrophication	Reduces emissions	Beneficial	Moderate	Solar emits much less
Mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Other: e.g., Cd, Pb, particulates	Reduces emissions	Beneficial	Moderate	Solar emits much less
Oil spills	Reduces risk	Beneficial	High	Note: BP Horizon Spill, Valdez Spill
Physical dangers				
Cooling water intake hazards	Eliminates hazard	Beneficial	Moderate	Thermoelectric cooling is relegated
Birds: flight hazards	Transmission lines	Detrimental	Low	Solar needs additional transmission line
Roadway and railway hazard	Reduces hazard	Beneficial	Low	Road and railway kill is likely reduced
Habitat				
Habitat fragmentation	Neutral	Neutral	Moderate	Needs research and observation
Local habitat quality	Reduces mining	Beneficial	Moderate	Mining vs. solar farms; needs research
Land transformation	Neutral	Neutral	Moderate	Needs research and observation
Climate change[a]	Reduce change	Beneficial	High	Solar emits ~25× less greenhouse gases

2.4. Water use, wastewater treatment and disposal

Water use in the electricity generation with PV in general, and with thin-film CdTe PV in particular was analyzed by Fthenakis et al. and Sinha et al. [3,4] respectively, and they have found that in any case, PV-generated electricity involves less water consumption and water withdrawal than any of the conventional, and most of the renewable energy generation options except for wind.

The industrial preparation and processing of CdTe PV modules involves the cadmium compounds CdTe, CdS and $CdCl_2$. First solar manufacturing wastewater contains up to 30 ppm of Cd, and standard metal precipitation technology removes Cd to approximately 100 ppb. First Solar adds filtration and ion exchange polishing technologies to reduce Cd levels to less than 20 ppb. Wastewater systems operate in a batch discharge mode. After treatment, water is collected in holding tanks, which are sampled and tested to confirm compliance to permit limits before discharging, and if not compliant, water is sent for re-treatment internally. First Solar factories are equipped with state-of-the-art analytical capability for in-house water testing of Cd. Figure 27 shows a process flow diagram of the wastewater treatment at First Solar manufacturing plants, and Figure 28 shows some of the equipment used at First Solar's dedicated wastewater treatment plant.

From 2009 to 2013, First Solar has reduced the amount of water necessary for manufacturing CdTe PV modules from 1.87 to 1.46 liters per Wp. Note that water withdrawal for CdTe PV manufacturing is lower than c-Si PV manufacturing due to a less energy and material intensive manufacturing process [3].

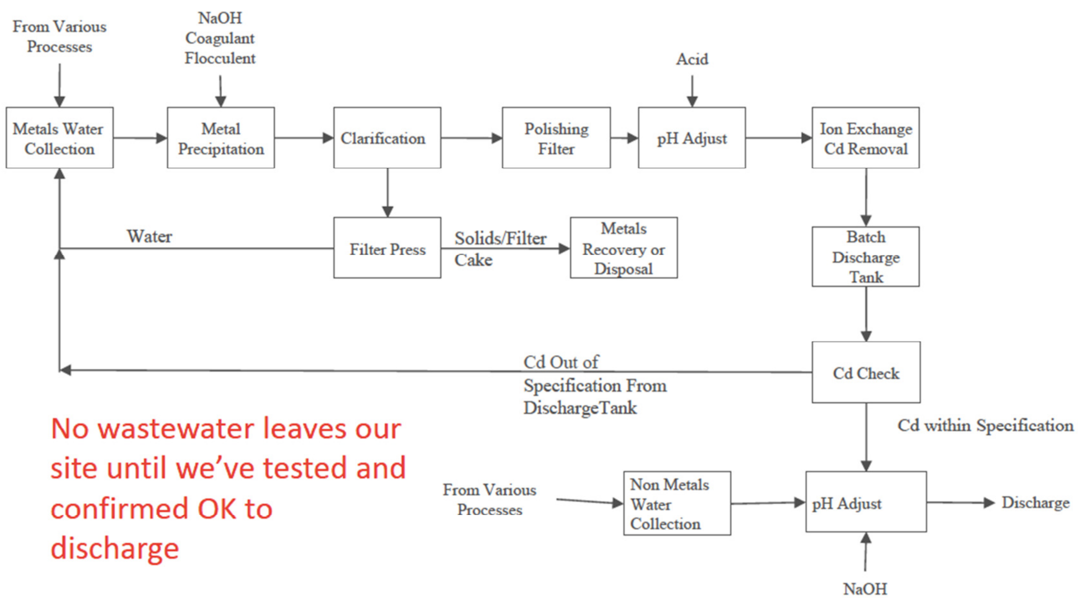

Figure 27: Process flow diagram of the wastewater treatment at First Solar manufacturing plants.

Figure 28: Equipment used at First Solar's dedicated wastewater treatment plant.

After treatment, First Solar Cd mass balance indicates that less than 0.02% of the total incoming Cd is released into water, and is well below regulatory final discharge limits.

3. Performance aspects of PV in warm climates

Less than 10% of PV systems worldwide are located in tropical regions [56]. With favorable irradiance conditions and the cost reductions experienced by PV technologies in recent years, installations in these areas of the world are expected to grow substantially in the near future. Irradiance, operating PV cell temperature and the spectral content of sunlight are the three most relevant parameters affecting the performance of PV devices in the field, and they can vary considerably from site to site, depending on whether a solar PV plant operates in the more traditional, temperate climate, PV markets, or in hot and sunny sites. Even at sunny sites with similar solar irradiation resource availability, wind speed influences PV module operating temperatures considerably and must be taken into account. Additionally, soiling issues are a matter of much greater concern in warm and sunny climates, and as different arid and desert sunny sites around the globe start to deploy PV plants in larger volumes, soiling needs to be addressed with greater care.

3.1. Performance of CdTe PV in hot and humid climates

Due to intrinsic material characteristics, thin-film CdTe and a-Si have been reported to present superior output performance in the field in sunny and warm climates [57,58]. With the considerable advances that CdTe PV has obtained in terms of both efficiency increases and manufacturing cost reductions, full-size commercial CdTe PV modules are currently double the efficiency of their a-Si counterparts. As operating temperatures in the field rise, all solar PV devices suffer performance losses, and among the commercially-available PV technologies, CdTe and a-Si are the ones with the lowest negative temperature coefficient of power, namely -0.25 to -0.34 %/^{o}C for CdTe [59] and -0.10 to -0.20 %/^{o}C for a-Si [36]. The more traditional crystalline silicon PV technologies have temperature coefficients ranging from -0.45 to -0.50 %/^{o}C, and might therefore suffer double the performance losses of their thin-film counterparts. Figure 29 shows the distribution of ambient and back-of-module surface temperatures measured in a First Solar PV array in the USA desert Southwest area.

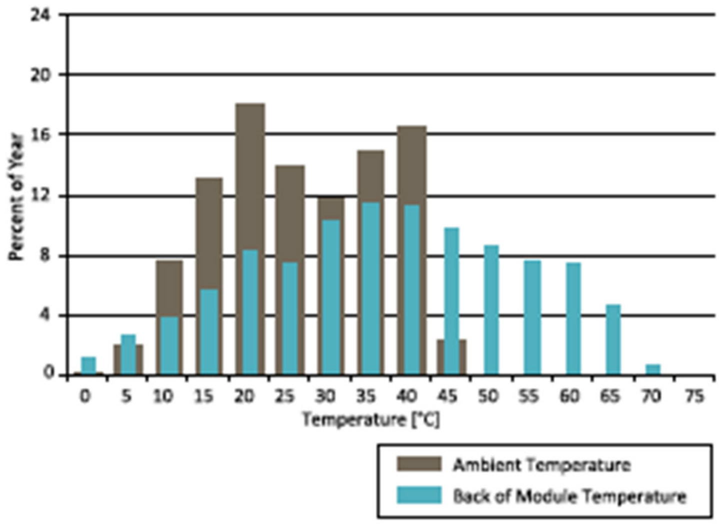

Figure 29: Distribution of ambient and back-of-module surface temperatures measured in a First Solar PV array in the USA desert Southwest area [58].

Figure 30 shows the distribution of the fraction of power production as a function of back-of-module temperatures for a First Solar PV power plant operating in the USA desert Southwest area.

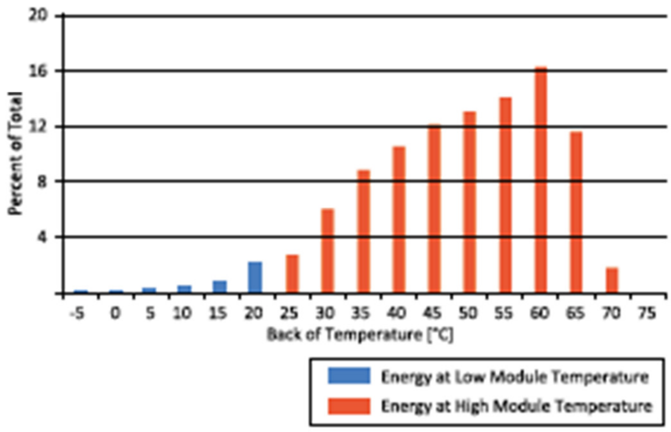

Figure 30: Distribution of the fraction of power production as a function of back-of-module temperatures for a First Solar PV power plant operating in the USA desert Southwest area [58].

These figures show that there is a considerable portion of time and energy produced by a PV system in a warm climate that is generated at temperature conditions far above the Standard Test Conditions of 25°C PV cell temperature. While these conditions indicate a superior performance expectation of First Solar's CdTe PV devices from a semiconductor characteristics point of view, they are also challenging from the standpoint of other PV device failure mechanisms, and First Solar is expecting to have slightly higher warranty failure rates in high-temperature climates. First Solar recommends a -0.7%/year long-term degradation rate in the modeling of long-term performance of CdTe systems in hot climates, instead of the -0.5%/year recommended in more temperate climates [58]. Going forward, First Solar has recently introduced a new cell structure with improved back-contact design that better manages the fundamental power output degradation mechanism inherent to CdTe PV devices. The improvement over plant lifetimes in long-term degradation rate afforded by the new back contact enables First Solar's long-term degradation guidance to be improved to –0.5% per annum for all climates [59].

3.2. Soiling

As PV develops into the multi-gigawatt range, the largest, utility-scale PV power plants are being installed in areas of the globe where soiling issues need to be taken into account. Soiling has been a matter of investigation at many sites worldwide, from Saudi Arabia [60] to the USA Southwest [61,62], and in the sunny Malaga region in Spain [63] and Kuwait [64], among many others.

The soiling of PV modules is an important issue regarding PV module power output. Anti-soiling coatings, which aim to reduce soiling losses, are a very interesting and promising topic [60]. Depending on the environmental conditions, the different surface structures and anti-reflection coatings which are applied on the glass in order to increase the annual gain of a PV module may turn non effective and glass transmittance may decrease below the level of unstructured or uncoated glass. Former investigations revealed enormous efficiency losses due to heavy soiling, up to -80% within a period of 6 months [60].

In the Brazilian emerging PV market, utility-scale PV power plants will also be deployed at sites where soiling will be an issue. Figures 31 and 32 show some examples of testing sites in the Brazilian Northeast where different PV module technologies are being deployed side by side to investigate soiling effects on PV system performance among other effects of operating solar farms in sunny and warm areas in Brazil.

Figure 31: Example of heavy, uniform soiling conditions at a PV test site in the Brazilian Southeast.

Many of the sunny sites in Brazil where PV power plants will be installed are also very windy sites, and PV power plants will often operate side by side with wind parks, as shown in Figure 32. An advantage of the windy sites is that PV modules will operate at lower temperatures and consequently suffer lower output losses due to temperature effects. However, wind also increases soiling, and promotes non-uniform distribution of soiling as shown in Figure 32, which might lead to adverse effects on performance that are often PV module design-, PV system electrical design- and layout-specific.

Figure 32: Examples of heavy, non-uniform soiling conditions at a PV test site in the Brazilian Southeast; non-uniformities in soiling patterns are mainly caused by strong wind conditions.

3.3. Reliability testing

In order for solar power to be able to compete with conventional electricity generation technologies, PV power plants have to reliably deliver power for 25-30 years, operating in the harsh environmental conditions in the field. PV module manufacturers offer product warranties of up to 10 years, and performance warranties are typically 25 years for 80% of the initial or nominal power. First solar maintains a reliability laboratory with first class ISO 17025 calibrated, automated equipment and data collection, and an extensive personnel training program. Table 3 shows some figures on the extensive reliability testing program currently in place at First Solar's manufacturing facilities in the USA and Malaysia, as well as at test sites around the world.

Table 3: Figures on First Solar's extensive testing of CdTe solar PV modules in the Perrysburg-OH manufacturing plant and elsewhere.

	Perrysburg	Global
Modules Tested Per Year	40,000 Modules	80,800 Modules
Modules Currently In Test	Over 1300 Modules	Over 4000 Modules
MW Tested Per Year	Over 3.5 MW	Over 4.4 MW
Reliability Lab Space	28,800 SqFt	64,300 SqFt

Recent advances in CdTe research and development have improved the long-term power-output degradation and extended reliability test performance of First Solar's thin-film CdTe PV modules. First Solar has recently introduced a new cell structure with improved back-contact design that better manages the fundamental power output degradation mechanism inherent to CdTe PV devices [59]. First Solar's proprietary 'Black' series module construction significantly enhances the long-term durability and extended test performance of the modules. The accelerated lab testing methods, field testing and associated analyses are carried in many sites around the globe. The advances in the solar cell performance, coupled with upgraded module materials, further substantiate the long-term power-generating capability of First Solar's CdTe PV modules in harsh operating conditions [59].

First Solar's reliability laboratory carries out activities in support of developments in high volume manufacturing (process monitoring), new product and process development, product reliability (new product and process qualification and certification, assistance in the preparation of technical notes and product data sheets, warranty (accrual predictions and field performance validation). The reliability lab capabilities include environmental (56 chambers) and light-soaking (143 chambers) facilities for accelerated testing of products and packages; static and dynamic loads to simulate wind, snow and ice loads at varying temperatures and rates; reverse current overload (RCOL), for determining the risk of fire under reverse current fault conditions; UV chamber, to accelerate UV exposure in order to evaluate materials and adhesive bonds susceptible to UV degradation; hail impact test, to verify PV module capability of withstanding the impact of hail; module breakage test, a safety test designed to provide confidence that cutting or piercing injuries are minimized when a PV module is broken; hot spot test, to determine the ability of a PV module to withstand heating effects caused by soiling or shading; impulse voltage test, to verify the capability of the solid insulation of the PV module to withstand over-voltages caused by a lightning strike; power characterization of PV modules at Standard Test Conditions and at varying temperature and irradiance conditions using a Class AAA solar simulator; wet & dry HiPot measurement facility, to evaluate the insulation of the PV module under wet operating conditions and verify that moisture does not enter the active parts; module thickness measurements, to characterize PV module thickness and relative shape; automated visual inspection, to detect any visual defects in the PV module; and near-IR measurements, to detect any defects in the module which are visible as a result of electroluminescence.

In addition to the above range of module reliability testing, First Solar has recently undertaken long-term parallel testing in recognition of the need to extend test durations to better differentiate PV modules in long-term field performance [59]. For example, in the Thresher Test, the conventional IEC test environmental stress exposure durations are multiplied by a factor of two to four in order to identify those modules with truly differentiated long-term reliability and performance. First Solar is the first thin-film PV manufacturer to pass the extended accelerated life cycle testing protocols of the Thresher Test and Long Term Sequential Test [65]. First Solar is also the first PV company to obtain the new VDE Quality Tested (QT) Certification for PV power plants (module and balance of system) [66].

3.4. Grid integration

The integration of utility-scale solar PV generators in the electricity grids worldwide represents at the same time an opportunity and a challenge. PV power plants that support grid stability and reliability are becoming available as PV generation grows to the point of making a significant contribution to the grid. Dynamic voltage regulation, active power management, ramp-rate control, frequency droop control and fault-ride-through capability are all aspects related to grid-friendly PV plants that are operational today [67]. Figure 33 shows a schematic diagram with an example of a plant control system and interfaces to other components, and Figure 34 shows an example of a large, utility-scale 290 MWp CdTe PV module power plant with grid-friendly plant control. The plant controller provides the following plant-level control functions:

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

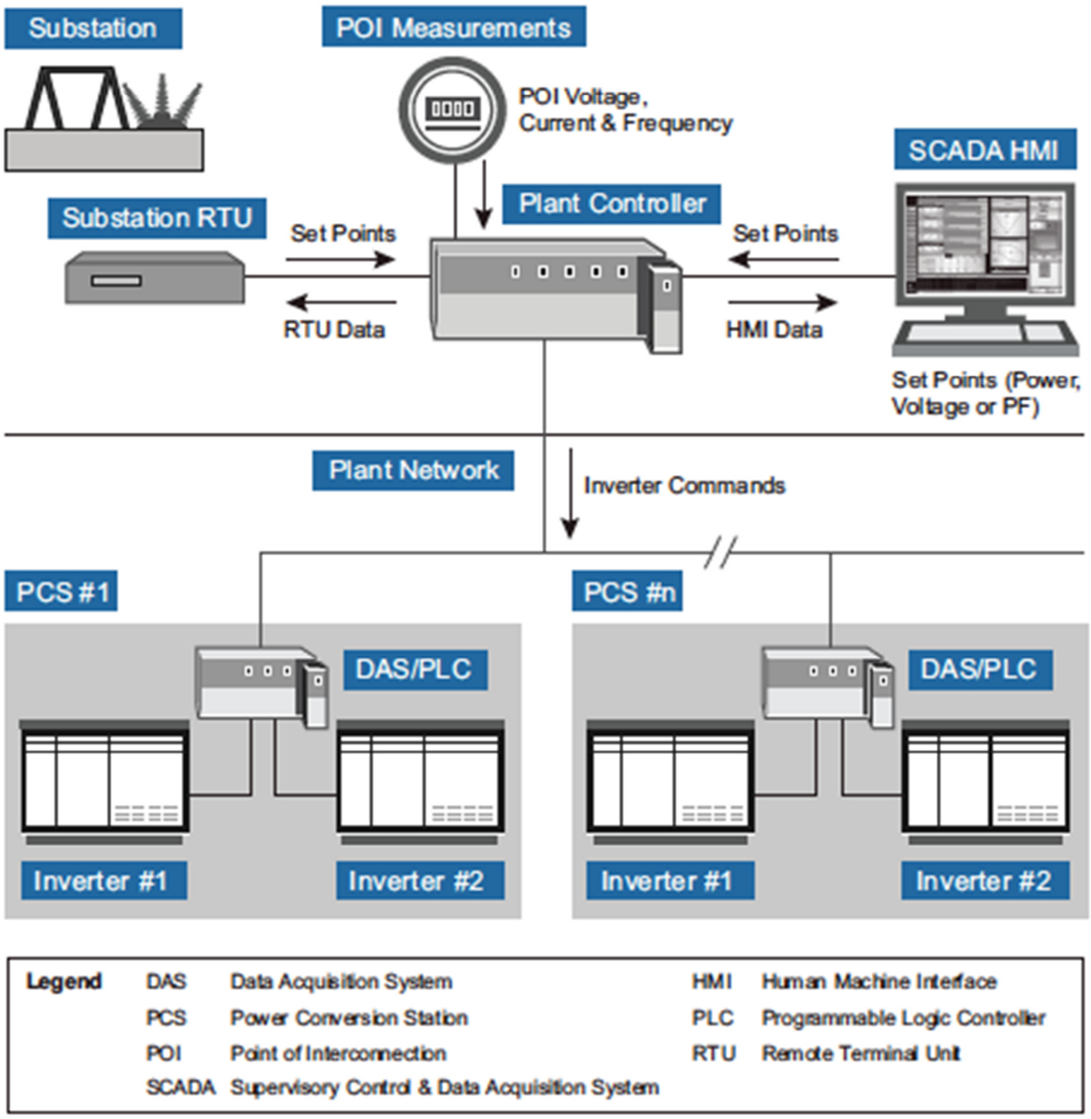

Figure 33: Example of a plant control system and interfaces to other components [67].

First Solar owns and operates a Solar Operations Center in Tempe-AZ, USA (Figure 35), from which it currently monitors the performance of over 2,000 MWp of CdTe PV power plants in the USA.

Figure 34: First Solar's Yuma County-Arizona, 290 MWp CdTe PV power plant with grid-friendly plant control [67].

Figure 35: First Solar Operations Center in Tempe, Arizona, from where the company controls over 2,000 MWp of solar power plants operating in the USA [67].

3.5. Field performance data

Utility-scale PV power plants are rapidly growing in size and number, but very little is reported publicly on the specific performance of large solar power plants and how their actual, measured output compares with common modeling tools that are used to price and sell the assets [68]. Typically, a PV power plant is sold largely on the basis of a calculation of the long-term average annual energy yield. One common strategy for generating long-term predictions uses satellite meteorological data and estimated loss assumptions along with a common simulation tool, such as PVSyst[17], to model the behavior of the power plant over a "typical" year. Panchula et al. [68] have compared the measured output performance of the Sarnia 20 MWp_{AC} power plant in Ontario, Canada after one year of continuous operation, to both the long-term energy prediction and the expected energy for the operating year 2010. Based on the first year's data, the power plant was shown to be operating 2.1% above the long-term prediction, well within the expected error-bars of the measurements.

In a long-term experiment with First Solar (formerly Solar Cells Inc.) 1995-vintage thin-film CdTe PV modules, after almost two decades of monitoring, the US National Renewable Energy Laboratory - NREL confirms the excellent reliability of First Solar's module technology, with no module failures in system operation [58]. Figure 36 shows the evolution of the DC power of the CdTe modules over 17 years (1995-2012), with a -0.53%/year degradation rate in the temperate climate of Colorado. USA.

The predicted energy ratio (PER) is the lifetime ratio of actual energy produced to the energy predicted. Figure 37 shows the average PER, by commissioning year, for 270MW (including >130MW of hot-climate deployments) of installed PV systems using First Solar CdTe modules. The PER substantiates First Solar's field performance record and validates First Solar's accuracy in predicting field performance. Current degradation guidance of –0.5%/year in temperate climates and –0.7%/year in high-temperature climates is First Solar's recommendation for long-term performance PV systems modeling [58]. As previously mentioned, First Solar's new cell structure with improved back-contact design enables First Solar's long-term degradation guidance to be improved to –0.5% per annum for all climates [59].

[17] http://www.pvsyst.com/en/

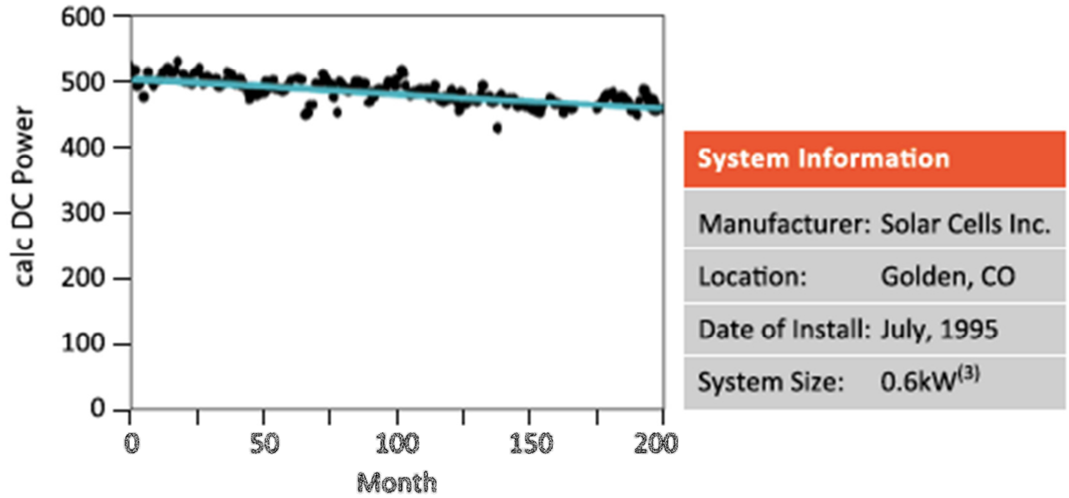

Figure 36: Long-term performance assessment of First Solar (formerly Solar Cells Inc.) CdTe PV modules carried out by the National Renewable Energy Laboratory – NREL, from 1995 to 2012. Annual output power degradation rate is 0.53%/year [58].

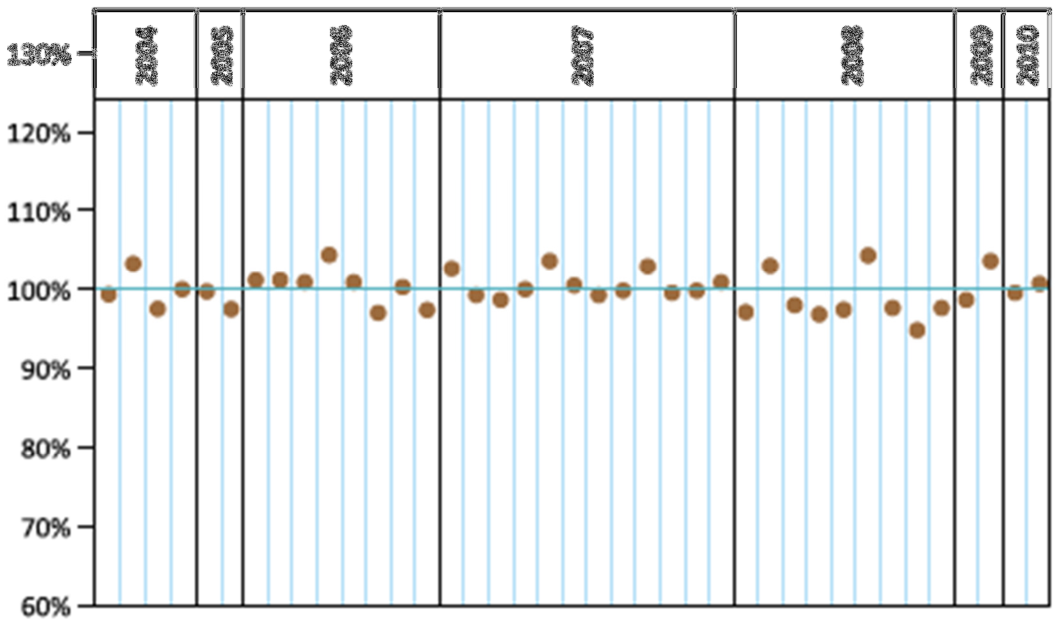

Figure 37: Average Predicted Energy Ratio – PER, by commissioning year, for 270MW of thin-film CdTe PV systems using First Solar modules: >270MW monitored installations base, including >130MW of hot-climate deployments [58].

References and further reading

The following list contains all references to published and publicly-available literature cited in this report, including the previous 12 peer review reports (references [16-27]) carried out on behalf of First Solar by independent experts in the USA (2003), the European Union (2005), France (2009), Spain (2010), India (2012), Italy (2012), the Middle East (2012), Germany (2012), Japan (2012), Thailand (2012), China (2013) and Chile (2013).

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