WIKIPEDIA

Cadmium telluride photovoltaics

Cadmium telluride (CdTe) photovoltaics describes a photovoltaic (PV) technology that is based on the use of cadmium telluride, a thin semiconductor layer designed to absorb and convert sunlight into electricity.[1] Cadmium telluride PV is the only thin film technology with lower costs than conventional solar cells made of crystalline silicon in multi-kilowatt systems.[1][2][3]

PV array made of cadmium telluride (CdTe) solar panels

On a lifecycle basis, CdTe PV has the smallest carbon footprint, lowest water use and shortest energy payback time of any current photo voltaic technology.[4][5][6] CdTe's energy payback time of less than a year allows for faster carbon reductions without short-term energy deficits.

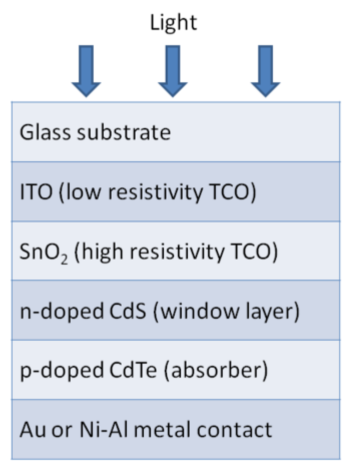
The toxicity of cadmium is an environmental concern mitigated by the recycling of CdTe modules at the end of their life time,[7] though there are still uncertainties[8][9] and the public opinion is skeptical towards this technology.[10][11] The usage of rare materials may also become a limiting factor to the industrial scalability of CdTe technology in the mid-term future. The abundance of tellurium—of which telluride is the anionic form—is comparable to that of platinum in the earth's crust and contributes significantly to the module's cost.[12]

CdTe photovoltaics are used in some of the world's largest photovoltaic power stations, such as the Topaz Solar Farm. With a share of 5.1% of worldwide PV production, CdTe technology accounted for more than half of the thin film market in 2013.[13] A prominent manufacturer of CdTe thin film technology is the company First Solar, based in Tempe, Arizona.

Contents

Background

The dominant PV technology has always been based on crystalline silicon wafers. Thin films and concentrators were early attempts to lower costs. Thin films are based on using thinner semiconductor layers to absorb and convert sunlight. Concentrators lower the number of panels by using lenses or mirrors to put more sunlight on each panel.



Cross-section of a CdTe thin film solar cell.

The first thin film technology to be extensively developed was amorphous silicon. However, this technology suffers from low efficiencies and slow deposition rates (leading to high capital costs). Instead, the PV market reached some 4 gigawatts in 2007 with crystalline silicon comprising almost 90% of sales.[14] The same source estimated that about 3 gigawatts were installed in 2007.

During this period cadmium telluride and copper indium diselenide or CIS-alloys remained under development. The latter is beginning to be produced in volumes of 1–30 megawatts per year due to very high, small-area cell efficiencies approaching 20% in the laboratory.[15] CdTe cell efficiency is approaching 20% in the laboratory with a record of 22.1% as of 2016.[16]

History

Research in CdTe dates back to the 1950s,[17][18][19][20][21][22] because its band gap (~1.5 eV) is almost a perfect match 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 cadmium sulfide (CdS). The cell was completed by adding top and bottom contacts. Early leaders in CdS/CdTe cell efficiencies were GE in the 1960s, and then Kodak, Monosolar, Matsushita, and AMETEK.

By 1981, Kodak used close spaced sublimation (CSS) and made the first 10% cells and first multi-cell devices (12 cells, 8% efficiency, 30 cm^2).[23] Monosolar[24] and AMETEK[25] used electrodeposition, a popular early method. Matsushita started with screen printing but shifted in the 1990s to CSS. Cells of about 10% sunlight-to-electricity efficiency were produced by the early 1980s at Kodak, Matsushita, Monosolar and AMETEK.[26]

An important step forward occurred when cells were scaled-up in size to make larger area products called modules. These products required higher currents than small cells and it was found that an additional layer, called a transparent conducting oxide (TCO), could facilitate the movement of current across the top of the cell (instead of a metal grid). One such TCO, tin oxide, was available for other uses (thermally reflective windows). Made more conductive for PV, tin oxide became and remains the norm in CdTe PV modules.


The utility-scale Waldpolenz Solar Park in Germany uses CdTe PV modules

CdTe cells achieved above 15% in 1992 by adding a buffer layer to the TCO/CdS/CdTe stack and then thinned the CdS to admit more light. Chu used resistive tin oxide as the buffer layer and then thinned the CdS from several micrometres to under half a micrometre in thickness. Thick CdS, as it was used in prior devices, blocked about 5 mA/cm^2 of light, or about 20% of the light usable by a CdTe device. The additional layer did not compromise the device's other properties.[26]

In the early 1990s, other players experienced mixed results.[26] Golden Photon held the record for a short period for the best CdTe module measured at NREL at 7.7% using a spray deposition technique. Matsushita claimed an 11% module efficiency using CSS and then dropped the technology. A similar efficiency and fate eventually occurred at BP Solar. BP used electrodeposition (inherited from Monosolar by a circuitous route when it purchased SOHIO, Monosolar's acquirer). BP Solar dropped CdTe in November 2002.[27] Antec was able to make about 7%-efficient modules, but went bankrupt when it started producing commercially during a short, sharp market downturn in 2002. However, as of 2014 Antec still made CdTe PV modules.[28]

CdTe start-ups include Calyxo[29] (formerly owned by Q-Cells), *PrimeStar Solar*, in Arvada, Colorado (acquired by First Solar from GE),[30] Arendi (https://web.archive.org/web/20081013032555/http://www.arendi.eu/) (Italy). Including Antec, their total production represents less than 70 megawatts per year.[31] Empa, the Swiss Federal Laboratories for Materials Testing and Research, focuses on the development of CdTe solar cells on flexible substrates and demonstrated cell efficiencies of 13.5% and 15.6% for flexible plastic foil and glass substrates, respectively.[32]

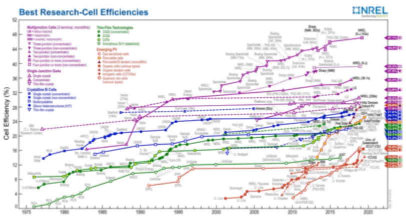
SCI and First Solar

The major commercial success was by Solar Cells Incorporated (SCI). Its founder, Harold McMaster, envisioned low-cost thin films made on a large scale. After trying amorphous silicon, he shifted to CdTe at the urging of Jim Nolan and founded Solar Cells Inc., which later became First Solar.[33] McMaster championed CdTe for its high-rate, high-throughput processing. SCI shifted from an adaptation of the CSS method then shifted to vapor transport.[34] In February 1999, McMaster sold the company to True North Partners, who named it First Solar.[35]

In its early years First Solar suffered setbacks, and initial module efficiencies were modest, about 7%. Commercial product became available in 2002. Production reached 25 megawatts in 2005.[36] The company manufactured in Perrysburg, Ohio and Germany.[37] In 2013, First Solar acquired GE's thin film solar panel technology in exchange for a 1.8% stake in the company.[38] Today, First Solar manufactures over 3 gigawatts with an average module efficiency of 16.4% in 2016.[39]

Technology

Cell efficiency



Solar cell efficiencies

In August 2014 First Solar announced a device with 21.1% conversion efficiency.[40] In February 2016, First Solar announced that they had reached a record 22.1% conversion efficiency in their CdTe cells. In 2014, the record module efficiency was also raised by First Solar from 16.1% up to 17.0%.[41] At this time, the company projected average production line module efficiency for its CdTe PV to be 17% by 2017, but by 2016, they predicted a module efficiency closer to ~19.5%.[42][43]

Since CdTe has the optimal band gap for single-junction devices, efficiencies close to 20% (such as already shown in CIS alloys) may be achievable in practical CdTe cells.[44]

Process optimization

Process optimization improved throughput and lowered costs. Improvements included broader substrates (since capital costs scale sublinearly and installation costs can be reduced), thinner layers (to save material, electricity, and processing time), and better material utilization (to save material and cleaning costs). 2014 CdTe module costs were about $72 per 1 square metre (11 sq ft),[45] or about $90 per module.

Ambient temperature

Module efficiencies are measured in laboratories at standard testing temperatures of 25 °C, however in the field modules are often exposed to much higher temperatures. CdTe's relatively low temperature coefficient protects performance at higher temperatures.[46][47][48] CdTe PV modules experience half the reduction of crystalline silicon modules, resulting in an increased annual energy output of 5-9%.[49]

Solar tracking

Almost all thin film photovoltaic module systems to-date have been non-solar tracking, because module output was too low to offset tracker capital and operating costs. But relatively inexpensive single-axis tracking systems can add 25% output per installed watt.[50] In addition, depending on the Tracker Energy Gain, the overall eco-efficiency of the PV system can be enhanced by lowering both system costs and environmental impacts.[51] This is climate-dependent. Tracking also produces a smoother output plateau around midday, better matching afternoon peaks.

Materials

Cadmium

Cadmium (Cd), a toxic heavy metal considered a hazardous substance, is a waste byproduct of mining, smelting and refining sulfidic ores of zinc during zinc refining, and therefore its production does not depend on PV market demand. CdTe PV modules provide a beneficial and safe use for cadmium that would otherwise be stored for future use or disposed of in landfills as hazardous waste. Mining byproducts can be converted into a stable CdTe compound and safely encapsulated inside CdTe PV solar modules for years. A large growth in the CdTe PV sector has the potential to reduce global cadmium emissions by displacing coal and oil power generation.[52]

Tellurium

Tellurium (Te) production and reserves estimates are subject to uncertainty and vary considerably. Tellurium is a rare, mildly toxic metalloid that is primarily used as a machining additive to steel. Te is almost exclusively obtained as a by-product of copper refining, with smaller amounts from lead and gold production. Only a small amount, estimated to be about 800 metric tons[53] per year, is available. According to USGS, global production in 2007 was 135 metric tons.[54] One gigawatt (GW) of CdTe PV modules would require about 93 metric tons (at current efficiencies and thicknesses).[55] Through improved material efficiency and increased PV recycling, the CdTe PV industry has the potential to fully rely on tellurium from recycled end-of-life modules by 2038.[56] In the last decade, new supplies have been located, e.g., in Xinju, China[57] as well as in Mexico and Sweden.[58] In 1984 astrophysicists identified tellurium as the universe's most abundant element having an atomic number over 40.[59][60] Certain undersea ridges are rich in tellurium.[60][61]

Cadmium chloride/magnesium chloride

The manufacture of a CdTe cell includes a thin coating with cadmium chloride ($CdCl_2$) to increase the cell's overall efficiency. Cadmium chloride is toxic, relatively expensive and highly soluble in water, posing a potential environmental threat during manufacture. In 2014 research discovered that abundant and harmless magnesium chloride ($MgCl_2$) performs as well as cadmium chloride. This research may lead to cheaper and safer CdTe cells.[62][63]

Safety

By themselves, cadmium and tellurium are toxic and carcinogenic, but CdTe forms a crystalline lattice that is highly stable, and is several orders of magnitude less toxic than cadmium.[64] The glass plates surrounding CdTe material sandwiched between them (as in all commercial modules) seal during a fire and do not allow any cadmium release unless the glass is broken.[65][66] All other uses and exposures related to cadmium are minor and similar in kind and magnitude to exposures from other materials in the broader PV value chain, e.g., to toxic gases, lead solder, or solvents (most of which are not used in CdTe manufacturing).[67][68]

Recycling

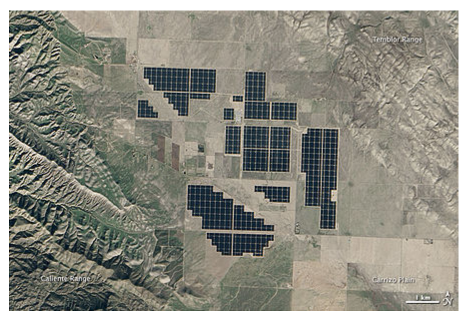
Due to the exponential growth of photovoltaics the number of worldwide installed PV systems has increased significantly. First Solar established the first global and comprehensive recycling program in the PV industry in 2005. Its recycling facilities operate at each of First Solar's manufacturing plants and recover up to 95% of semiconductor material for reuse in new modules and 90% of glass for reuse in new glass products.[69][70] A life cycle assessment of CdTe module recycling by the University of Stuttgart showed a reduction in primary energy demand in End-Of-Life from 81 MJ/m^2 to -12 MJ/m^2, a reduction of around 93 MJ/m^2, and in terms of global warming potential from 6 kg CO_2-equiv./m^2 to -2.5 CO_2-equiv./m^2, a reduction of around -8.5 CO_2-equiv./m^2. These reductions show a highly beneficial change in the overall environmental profile of CdTe photovoltaic module. The LCA also showed that the main contributors to considered environmental impact categories are due to required chemicals and energy within the processing of CdTe modules.[71]

Grain boundaries

Grain boundary is the interface between two grains of a crystalline material and occur when two grains meet. They are a type of crystalline defect. It is often assumed that the open-circuit voltage gap seen in CdTe, in comparison to both single crystal GaAs and the theoretical limit, may be in some way attributable to the grain boundaries within the material. There have however been a number of studies which have suggested not only that GBs are not deleterious to performance but may in fact be beneficial as sources of enhanced carrier collection.[72] So, the exact role of the grain boundaries in limitation of performance of CdTe-based solar cells remains unclear and the research is ongoing to address this question.

Market viability

Success of cadmium telluride PV has been due to the low cost achievable with the CdTe technology, made possible by combining adequate efficiency with lower module area costs. Direct manufacturing cost for CdTe PV modules reached $0.57 per watt in 2013,[73] and capital cost per new watt of capacity is near $0.9 per watt (including land and buildings).[74]



The Topaz Solar Farm employs 9 million CdTe-modules. It was the world's largest PV power station in 2014.

Notable systems

Utility-scale CdTe PV solutions were claimed to be able to compete with peaking fossil fuel generation sources depending on irradiance levels, interest rates and other factors such as development costs.[75] Recent installations of large First Solar CdTe PV systems were claimed to be competitive with other forms of solar energy:

- First Solar's 290-megawatt (MW) Agua Caliente project in Arizona is one of the largest photovoltaic power station ever built. Agua Caliente features First Solar's plant control, forecasting and energy scheduling capabilities that contribute to grid reliability and stability.[76][77]
- The 550 MW Topaz Solar Farm in California, finished construction in November 2014 and was the world's largest solar farm at the time.[78]

- First Solar's 13 MW project in Dubai, operated by the Dubai Electricity and Water Authority, is the first part of the Mohammed bin Rashid Al Maktoum Solar Park, and was the region's largest PV power plant at the time of completion in 2013.[78]
- A 40 MW system installed by Juwi group in Waldpolenz Solar Park, Germany, at the time of its announcement, was the world's largest and lowest cost planned PV system. The price was 130 million euros.[79]
- A 128 MWp system installed by Belectric at Templin, Brandenburg, Germany is the current largest thin-film PV installation in Europe (as of January 2015).[80]
- For the 21 MW Blythe Photovoltaic Power Plant in California, a power purchase agreement fixed the price for the generated electricity at $0.12 per kWh (after the application of all incentives).[81] Defined in California as the "Market Referent Price," this set the price the PUC would pay for any daytime peaking power source, e.g., natural gas. Although PV systems are intermittent and not dispatchable the way natural gas is, natural gas generators have an ongoing fuel price risk that PV does not have.
- A contract for two megawatts of rooftop installations with Southern California Edison. The SCE program is designed to install 250 MW at a total cost of $875M (averaging $3.5/watt), after incentives.[82]

See also

- Abound Solar
- Cadmium telluride
- Copper indium gallium selenide (CIGS).
- Energy harvesting
- First Solar
- High efficiency solar cells
- Low cost solar cell
- Renewable energy
- Solar cell
- Solar energy
- Solar panel
- Thin film solar cell

References and notes

1. "Publications, Presentations, and News Database: Cadmium Telluride" (https://www.nrel.gov/pv/cadmium-telluride-solar-cells.html). National Renewable Energy Laboratory.
2. K. Zweibel, J. Mason, V. Fthenakis, "A Solar Grand Plan (http://www.sciam.com/article.cfm?id=a-solar-grand-plan)", *Scientific American*, Jan 2008. CdTe PV is the cheapest example of PV technologies and prices are about 16¢/kWh with US Southwest sunlight.
3. Further mention of cost competitiveness: "Solar Power Lightens Up with Thin-Film Technology (http://www.sciam.com/article.cfm?id=solar-power-lightens-up-with-thin-film-cells)", *Scientific American*, April 2008.
4. Peng et al. (2013). "Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems". *Renewable and Sustainable Energy Reviews*. **19**: 255–274. doi:10.1016/j.rser.2012.11.035 (https://doi.org/10.1016%2Fj.rser.2012.11.035). hdl:10397/34975 (https://hdl.handle.net/10397%2F34975).
5. V. Fthenakis and H. C. Kim. (2010). "Life-cycle uses of water in U.S. electricity generation". *Renewable and Sustainable Energy Reviews*. **14** (7): 2039–2048. doi:10.1016/j.rser.2010.03.008 (https://doi.org/10.1016%2Fj.rser.2010.03.008).

6. de Wild-Scholten, Mariska (2013). "Energy payback time and carbon footprint of commercial photovoltaic systems". *Solar Energy Materials & Solar Cells*. **119**: 296–305. doi:10.1016/j.solmat.2013.08.037 (https://doi.org/10.1016%2Fj.solmat.2013.08.037).
7. Fthenakis, Vasilis M. (2004). "Life cycle impact analysis of cadmium in CdTe PV production" (http://www.clca.columbia.edu/papers/Life_Cycle_Impact_Analysis_Cadmium_CdTe_Photovoltaic_production.pdf) (PDF). *Renewable and Sustainable Energy Reviews*. **8** (4): 303–334. doi:10.1016/j.rser.2003.12.001 (https://doi.org/10.1016%2Fj.rser.2003.12.001). Archived (https://web.archive.org/web/20140508202733/http://www.clca.columbia.edu/papers/Life_Cycle_Impact_Analysis_Cadmium_CdTe_Photovoltaic_production.pdf) (PDF) from the original on 8 May 2014.
8. Werner, Jürgen H. (2 November 2011). "Toxic Substances In Photovoltaic Modules" (https://web.archive.org/web/20141221045847/http://www.postfreemarket.net/pdf/japan1.pdf) (PDF). *postfreemarket.net*. Institute of Photovoltaics, University of Stuttgart, Germany - The 21st International Photovoltaic Science and Engineering Conference 2011 Fukuoka, Japan. p. 2. Archived from the original (http://www.postfreemarket.net/pdf/japan1.pdf) (PDF) on 21 December 2014. Retrieved 23 September 2014.
9. "Water Solubility of Cadmium Telluride in a Glass-to-Glass Sealed PV Module" (https://web.archive.org/web/20150626130245/http://postfreemarket.net/wp-content/uploads/2015/01/cdtecomplete.pdf) (PDF). Vitreous State Laboratory, and AMELIO Solar, Inc. 2011. Archived from the original (http://postfreemarket.net/wp-content/uploads/2015/01/cdtecomplete.pdf) (PDF) on 2015-06-26.
10. "The Lowdown on the Safety of First Solar's CdTe Thin Film" (http://www.greentechmedia.com/articles/read/how-safe-is-first-solars-cdte-thin-film/). *greentechmedia.com*.
11. Guest Column. "Cadmium: The Dark Side of Thin-Film?" (http://gigaom.com/2008/09/25/cadmium-the-dark-side-of-thin-film/). *gigaom.com*.
12. "NREL: Manufacturing Analysis - Supply Constraints Analysis" (https://web.archive.org/web/20141221043003/http://www.nrel.gov/analysis/key_activities_jobs_sup_cstr.html). *nrel.gov*. Archived from the original (http://www.nrel.gov/analysis/key_activities_jobs_sup_cstr.html) on 2014-12-21. Retrieved 2014-12-21.
13. Fraunhofer ISE Photovoltaics Report (http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf), July 28, 2014, pages 18,19
14. Various estimates of world module production in 2007 (http://worldwatch.org/node/5449#notes) Archived (https://web.archive.org/web/20110725035832/http://worldwatch.org/node/5449) 2011-07-25 at the Wayback Machine
15. "NREL: News - Record Makes Thin-Film Solar Cell Competitive with Silicon Efficiency" (http://www.nrel.gov/news/press/2008/574.html). *nrel.gov*.
16. http://investor.firstsolar.com/news-releases/news-release-details/first-solar-achieves-yet-another-cell-conversion-efficiency
17. D. A. Jenny and R. H. Bube (1954). "Semiconducting CdTe". *Phys. Rev*. **96** (5): 1190–1191. Bibcode:1954PhRv...96.1190J (https://ui.adsabs.harvard.edu/abs/1954PhRv...96.1190J). doi:10.1103/PhysRev.96.1190 (https://doi.org/10.1103%2FPhysRev.96.1190).
18. R. H. Bube (1955). "Photoconductivity of the Sulfide, Selenide, and Telluride of Zinc or Cadmium". *Proceedings of the IRE*. **43** (12): 1836–1850. doi:10.1109/JRPROC.1955.278046 (https://doi.org/10.1109%2FJRPROC.1955.278046). ISSN 0096-8390 (https://www.worldcat.org/issn/0096-8390).
19. D. A. Cusano (1963). "CdTe Solar Cells and PV Heterojunctions in II-VI Compounds". *Solid State Electronics*. **6** (3): 217–218. Bibcode:1963SSEle...6..217C (https://ui.adsabs.harvard.edu/abs/1963SSEle...6..217C). doi:10.1016/0038-1101(63)90078-9 (https://doi.org/10.1016%2F0038-1101%2863%2990078-9).

20. B. Goldstein (1958). "Properties of PV Films of CdTe". *Phys. Rev.* **109** (2): 601–603. Bibcode:1958PhRv..109..601G (https://ui.adsabs.harvard.edu/abs/1958PhRv..109..601G). doi:10.1103/PhysRev.109.601.2 (https://doi.org/10.1103%2FPhysRev.109.601.2).
21. Y. A. Vodakov; G. A. Lomakina; G. P. Naumov; Y. P. Maslakovets (1960). "A P-N Junction photocell made of CdTe". *Soviet Physics, Solid State*. **2** (1): 1.
22. R. Colman, July 28, 1964 U.S. Patent 3,142,586 (https://www.google.com/patents/US3142586)
23. Y. S. Tyan, 1978, Polycrystalline thin film CdS/CdTe photovoltaic cell, Kodak, U.S. Patent 4,207,119 (https://www.google.com/patents/US4207119) (EP0006025); Y. S. Tyan and E. A. Perez-Albuerne, 1982, Integrated array of photovoltaic cells having minimized shorting losses, Kodak, U.S. Patent 4,315,096 (https://www.google.com/patents/US4315096). Tyan especially published both patents and papers of significance at Kodak and helped to establish CdTe as an important thin film option.
24. B. Basol, E. Tseng, R.L. Rod, 1981, Thin film heterojunction photovoltaic cells and methods of making the same, Monosolar U.S. Patent 4,388,483 (https://www.google.com/patents/US4388483). B. Basol patented numerous aspects of electrodeposition and CdTe contacting for Monosolar. Monosolar was subsequently bought by SOHIO, which was then absorbed by British Petroleum. Electrodeposition continued at BP Solar until about 2002 when it was canceled along with all thin film work at BP.
25. Peter Meyers, originally of Ametek, provides a thread stretching from Ametek through Solar Cells Inc. to First Solar. He is on Ametek patents U.S. Patent 4,260,427 (https://www.google.com/patents/US4260427), 1981; U.S. Patent 4,710,589 (https://www.google.com/patents/US4710589), 1987; and SCI/First Solar patents
26. K. Zweibel (1995). "Thin Films Past Present and Future" (https://www.osti.gov/bridge/servlets/purl/61140-cYAVRN/webviewable/61140.PDF) (PDF). *Nrel/Tp-413-7486*.R. Noufi and K. Zweibel (2006). *High-Efficiency CdTe and CIGS Thin-Film Solar Cells: Highlights and Challenges* (https://web.archive.org/web/20081007211436/http://www.nrel.gov/pv/thin_film/docs/wc4papernoufi__.doc). National Renewable Energy Laboratory, Golden, CO 80401, USA. Archived from the original (http://www.nrel.gov/pv/thin_film/docs/wc4papernoufi__.doc) on 2008-10-07. Retrieved 2008-10-09.
27. "BP solar ditches thin-film photovoltaics - IEEE Journals & Magazine" (https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1159741). *ieeexplore.ieee.org*. Retrieved 2018-05-20.
28. "Bunter ist besser" (http://www.antec-solar.de). *antec-solar.de*.
29. "Company—Yesterday to Tomorrow" (http://www.calyxo.com/en/company.html). *Calyxo*. Retrieved August 1, 2015. "2011/02 Solar Fields LLC takes over Q-Cells shares"
30. "First Solar Acquires GE's PrimeStar Solar IP, Misses Q2 Revenue and Lowers Guidance" (http://www.greentechmedia.com/articles/read/First-Solar-Misses-Q2-Revenue-Lowers-Guidance-Acquires-GEs-Primestar-Sol). *GrenntechMedia*. 6 August 2013.
31. "While First Solar keeps on trucking, others in CdTe thin-film PV pack keep on muddling" (http://www.fabtech.org/chip_shots/_a/while_first_solar_keeps_on_trucking_others_in_cdte_thin_film_pv_pack_keep_o/). Fabtech.org. 2008-08-21.
32. "Empa CdTe—Thin Films and Photovoltaics" (http://www.empa.ch/plugin/template/empa/1205/*/---/l=2). *Empa*. Retrieved 5 August 2015.
33. After long wait, McMaster to join hall of fame (http://www.toledoblade.com/Opinion/2008/04/29/After-long-wait-McMaster-to-join-hall-of-fame.html), April 29, 2008
34. SCI CSS patent: Foote et al. Process for making photovoltaic devices and resultant product, United States Patent 5248349; and their vapor transport patent, featuring the movement of vaporized cadmium and tellurium atoms through a closed, silicon carbide distributor: Apparatus and method for depositing a semiconductor material, United States Patent 6037241. Both are now owned by First Solar.

35. D. H. Rose; et al. (October 1999). *Technology Support of High-Throughput Processing of Thin Film CdTe Panels* (http://www.nrel.gov/docs/fy00osti/27149.pdf) (PDF). NREL SR-520-27149. p. Viii (preface).
36. "First Solar annual manufacturing levels" (http://www.firstsolar.com/images/sub_side/company_graph_en.gif). FirstSolar.com. 2008.
37. Friedman, Thomas L. (5 November 2009). *Hot, Flat, and Crowded: Why The World Needs A Green Revolution - and How We Can Renew Our Global Future* (https://books.google.com/books?id=Syd_mi25emQC). Penguin Books Limited. p. 388. ISBN 978-0-14-191850-1.
38. First Solar Gives GE 1.8% Stake in Thin-Film Partnership (https://www.bloomberg.com/news/2013-08-06/first-solar-buys-ge-s-cadmium-telluride-solar-property.html). bloomberg.com. 2013-08-07
39. "First Solar Annual Report" (http://investor.firstsolar.com/common/download/download.cfm?companyid=FSLR&fileid=936441&filekey=FF229006-19D1-4DC5-B7F3-AE92F8153C15&filename=First_Solar_Annual_Report_Web_Posting.pdf) (PDF).
40. "First Solar Builds the Highest Efficiency Thin Film PV Cell on Record" (https://web.archive.org/web/20140909083709/http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=864426). *firstsolar.com*. Archived from the original (http://investor.firstsolar.com/releasedetail.cfm?releaseid=864426) on 2014-09-09. Retrieved 2014-08-25.
41. "First Solar Sets Thin-Film Module Efficiency World Record of 17.0 Percent" (https://web.archive.org/web/20140320173449/http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=833971). *firstsolar.com*. Archived from the original (http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=833971) on 2014-03-20. Retrieved 2014-03-20.
42. Sinha, P. (2013). "Life cycle materials and water management for CdTe photovoltaics". *Solar Energy Materials & Solar Cells*. **119**: 271–275. doi:10.1016/j.solmat.2013.08.022 (https://doi.org/10.1016%2Fj.solmat.2013.08.022).
43. "First Solar Hits Record 22.1% Conversion Efficiency for CdTe Solar Cell" (https://www.greentechmedia.com/articles/read/First-Solar-Hits-Record-22.1-Conversion-Efficiency-For-CdTe-Solar-Cell). Retrieved 2016-11-08.
44. M. Gloeckler, I. Sankin, Z. Zhao (2013). "CdTe Solar Cells at the Threshold to 20%". *IEEE Journal of Photovoltaics*. **3** (4): 1389–1393. doi:10.1109/jphotov.2013.2278661 (https://doi.org/10.1109%2Fjphotov.2013.2278661).
45. This number is calculated by multiplying efficiency (12.6%) by 1000 to get output watts per square meter (126 W/m^2), and then multiplying power by the stated cost of $0.57 per watt to get $72/m^2
46. "Regenerative Energiesysteme" (http://www.volker-quaschning.de/publis/regen/index.php). *Hanser Verlag*. 2012.
47. P. Singh and N.M. Ravindra (June 2012). "Temperature Dependence of Solar Cell Performance—an Analysis". *Solar Energy Materials and Solar Cells*. **101**: 36–45. doi:10.1016/j.solmat.2012.02.019 (https://doi.org/10.1016%2Fj.solmat.2012.02.019).
48. Green, M. (August 2003). "General Temperature Dependence of Solar Cell Performance and Implications for Device Modelling". *Progress in Photovoltaics: Research and Applications*. **11** (5): 333–340. doi:10.1002/pip.496 (https://doi.org/10.1002%2Fpip.496).
49. N. Strevel, L. Trippel, M. Gloeckler (August 2012). "Performance characterization and superior energy yield of First Solar PV power plants in high temperature conditions" (http://dev.firstsolar.com/sitecore/shell/Controls/Rich%20Text%20Editor/~/media/Files/Products%20and%20Services%20-%20Product%20Documentation/Technology/PVI_17_Performance_FirstSolar_PV_Plants.ashx). *Photovoltaics International*.

50. "Parabolic Trough Technology Models and Software Tools" (https://web.archive.org/web/20080922195327/http://www.nrel.gov/csp/troughnet/models_tools.html#solaradvisormodel). 2008-07-25. Archived from the original (http://www.nrel.gov/csp/troughnet/models_tools.html#solaradvisormodel) on 2008-09-22. Retrieved 2008-10-14. Like any solar price model, the Solar Advisory Model is quite sensitive to assumptions. Different sunlight, tax rates, interest rates, discount rates, loan durations, temperature coefficients, annual degradation rates, initial de-rating versus standard conditions, inverter efficiencies and O&M, and others can each have as much as a 10% impact on costs per unit power.
51. P. Sinha and S. Dailey (November 2013). "Tracking systems boost eco-efficiency" (https://web.archive.org/web/20131213233100/http://www.solarindustrymag.com/issues/SI1311/FEAT_02_Tracking-Systems-Boost-Eco-Efficiency.html). *Solar Industry*. Archived from the original (http://www.solarindustrymag.com/issues/SI1311/FEAT_02_Tracking-Systems-Boost-Eco-Efficiency.html#) on 2013-12-13. Retrieved 2013-12-13.
52. M. Raugei and V. Fthenakis (2010). "Cadmium flows and emissions from CdTe PV: future expectations". *Energy Policy*. **38** (9): 5223–5228. doi:10.1016/j.enpol.2010.05.007 (https://doi.org/10.1016%2Fj.enpol.2010.05.007).
53. "Assessment of critical thin film resources" (https://web.archive.org/web/20090507182315/http://www.nrel.gov/pv/thin_film/docs/telluriumworldindustrialminerals2000.doc). Archived from the original (http://www.nrel.gov/pv/thin_film/docs/telluriumworldindustrialminerals2000.doc) (.doc file) on 2009-05-07.
54. "Tellurium" (http://minerals.usgs.gov/minerals/pubs/commodity/selenium/mcs-2008-tellu.pdf) (PDF). *Mineral Commodity Summaries*. United States Geological Survey. January 2008.
55. "First Solar CdTe Photovoltaic Technology: Environmental, Health and Safety Assessment" (http://www.firstsolar.com/-/media/Documents/Sustainability/Peer-Reviews/Chile-Peer-Review---Cener_EN.ashx). National Renewable Energy Centre. October 2013. p. 32.
56. Max Marwede and Armin Reller (2012). "Future recycling flows of tellurium from cadmium telluride photovoltaic waste" (https://depositonce.tu-berlin.de/bitstream/11303/7375/3/2012_marwede_et-al.pdf) (PDF). *Resources, Conservation, & Recycling*. **69** (4): 35–49. doi:10.1016/j.resconrec.2012.09.003 (https://doi.org/10.1016%2Fj.resconrec.2012.09.003).
57. Publications of the Sichuan Xinju Mineral Resource Development Co., China
58. Zweibel, K. (2010). "The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics". *Science*. **328** (5979): 699–701. Bibcode:2010Sci...328..699Z (https://ui.adsabs.harvard.edu/abs/2010Sci...328..699Z). doi:10.1126/science.1189690 (https://doi.org/10.1126%2Fscience.1189690). PMID 20448173 (https://www.ncbi.nlm.nih.gov/pubmed/20448173).
59. B. L. Cohen (1984). "Anomalous behavior of tellurium abundances". *Geochimica et Cosmochimica Acta*. **48** (1): 204–205. Bibcode:1984GeCoA..48..203C (https://ui.adsabs.harvard.edu/abs/1984GeCoA..48..203C). doi:10.1016/0016-7037(84)90363-6 (https://doi.org/10.1016%2F0016-7037%2884%2990363-6).
60. Hein, J. (2004). "Chapter 5 from Workshop on Minerals other than Polymetallic Nodules of the International Seabed Area". *Cobalt-Rich Ferromanganese Crusts: Global Distribution, Composition, Origin and Research Activities*. Kingston, Jamaica: Office of Resource and Environmental Monitoring, International Seabed Authority. ISBN 978-976-610-647-8. "It has been suggested that Te is unique in the universe in that its cosmic abundance is as great or greater than any of other element with an atomic number higher than 40, yet it is one of the least abundant elements in the Earth’s crust and in ocean water.""

61. Hein, J.; Koschinsky, A.; Halliday, A. (2003). "Global Occurrence of tellurium-rich ferromanganese crusts and a model for enrichment of tellurium". *Geochimica et Cosmochimica Acta*. **67** (6): 1117–1127. Bibcode:2003GeCoA..67.1117H (https://ui.adsabs.harvard.edu/abs/2003GeCoA..67.1117H). doi:10.1016/s0016-7037(02)01279-6 (https://doi.org/10.1016%2Fs0016-7037%2802%2901279-6). "The ridges occur at 400-4000 m depths where currents have kept the rocks swept clean of sediments for millions of years. Crusts…forming pavements up to 250 mm thick"
62. Karen Field. "Bean Curd Component Could Slash Solar Panel Costs" (http://www.eetimes.com/document.asp?doc_id=1322906). EE Times. 2014.
63. Major, J. D.; Treharne, R. E.; Phillips, L. J.; Durose, K. (2014). "A low-cost non-toxic post-growth activation step for Cd *Te* solar cells". *Nature*. **511** (7509): 334–337. Bibcode:2014Natur.511..334M (https://ui.adsabs.harvard.edu/abs/2014Natur.511..334M). doi:10.1038/nature13435 (https://doi.org/10.1038%2Fnature13435). PMID 25030171 (https://www.ncbi.nlm.nih.gov/pubmed/25030171).
64. "The Lowdown on the Safety of First Solar's CdTe Thin Film" (https://www.greentechmedia.com/articles/read/how-safe-is-first-solars-cdte-thin-film). Retrieved 2016-11-08.
65. V. Fthenakis, M. Fuhrmann, J. Heiser, W. Wang (2004). *Experimental Investigation of Emissions and Redistribution of Elements in CdTe PV Modules during Fires* (https://web.archive.org/web/20081007225101/http://www.nrel.gov/pv/thin_film/docs/fthenakis_2004_cdte_fires_paris_preprint.pdf) (PDF). 19th European PV Solar Energy Conference. Paris, France. Archived from the original (http://www.nrel.gov/pv/thin_film/docs/fthenakis_2004_cdte_fires_paris_preprint.pdf) (PDF) on 2008-10-07.
66. Beckmann and Mennenga (2011). "Calculation of emissions when there is a fire in a photovoltaic system made of cadmium telluride modules". Bavarian Environmental Protection Agency.
67. V. Fthenakis, H. C. Kim (2006). "CdTe Photovoltaics: Life Cycle Environmental Profile and Comparisons" (https://zenodo.org/record/1259413). *European Material Research Society Meeting, Symposium for Environmental Issues*. **515** (15): 5961–5963. Bibcode:2007TSF...515.5961F (https://ui.adsabs.harvard.edu/abs/2007TSF...515.5961F). doi:10.1016/j.tsf.2006.12.138 (https://doi.org/10.1016%2Fj.tsf.2006.12.138).
68. D. H. Rose; et al. (1999). "Technology Support of High-Throughput Processing of Thin Film CdTe Panels" (http://www.nrel.gov/docs/fy00osti/27149.pdf) (PDF). NREL.
69. "Evolution of First Solar's Module Recycling Program" (http://iea-pvps.org/fileadmin/dam/public/workshop/07_Andreas_WADE.pdf) (PDF). *FirstSolar*. 2013. p. 2. Retrieved July 28, 2015.
70. ftp://ftp.co.imperial.ca.us/icpds/eir/campo-verde-solar/final/life-cycle-cdte.pdf
71. Held, M. (2009-11-18). "Life Cycle Assessment of CdTe PV Module Recycling". *24th European Photovoltaic Solar Energy Conference, 21–25 September 2009, Hamburg, Germany*. 21-25 September 2009: 2370–2375. doi:10.4229/24thEUPVSEC2009-3CO.7.4 (https://doi.org/10.4229%2F24thEUPVSEC2009-3CO.7.4).
72. Major, Jonathan D. (2016). "Grain boundaries in CdTe thin film solar cells: A review". *Semiconductor Science and Technology*. **31** (9): 093001. Bibcode:2016SeScT..31i3001M (https://ui.adsabs.harvard.edu/abs/2016SeScT..31i3001M). doi:10.1088/0268-1242/31/9/093001 (https://doi.org/10.1088%2F0268-1242%2F31%2F9%2F093001).
73. "First Solar Reports Largest Quarterly Decline In CdTe Module Cost Per-Watt Since 2007" (http://cleantechnica.com/2013/11/07/first-solar-reports-largest-quarterly-decline-cdte-module-cost-per-watt-since-2007/). *CleanTechnica*.
74. Pacific Crest Presentation, August 3–5, 2008 (http://wsw.com/webcast/pc13/fslr/)
75. "Grid-connected bulk power systems" (http://www.firstsolar.com/Our-Solutions/UtilityScaleGeneration). *website*. First Solar.

76. "Agua Caliente (limited access)" (http://www.firstsolar.com/Projects/Agua-Caliente-Solar-Project). First Solar.
77. http://www.power-technology.com The world's biggest solar power plants (http://www.power-technology.com/features/feature-largest-solar-power-plants-in-the-world/), 29 August 2013
78. "Projects" (http://www.firstsolar.com/en/about-us/projects/topaz-solar-farm). First Solar.
79. "Report at juwi.de" (https://web.archive.org/web/20120113060231/http://www.pennwd.com/htdocs/PDFs/Feb07Solar-PressRelease.pdf) (PDF). Archived from the original (http://www.pennwd.com/htdocs/PDFs/Feb07Solar-PressRelease.pdf) (PDF) on 2012-01-13. (401 KB)
80. "Belectric press announcement" (https://web.archive.org/web/20150113190219/http://www.belectric.com/fileadmin/MASTER/pdf/press_releases/pm_BEL_2013_0422_Inbetriebnahme_Templin_EN.pdf) (PDF). Archived from the original (http://www.belectric.com/fileadmin/MASTER/pdf/press_releases/pm_BEL_2013_0422_Inbetriebnahme_Templin_EN.pdf) (PDF) on 2015-01-13. Retrieved 2015-01-06. (525 KB)
81. "First Solar announces two solar projects with Southern California Edison" (http://www.semiconductor-today.com/news_items/2008/JULY/FIRSTSOLAR_170708.htm). Semiconductor-Today.com. 2008-07-17.
82. "California Utility to Install 250MW of Roof-Top Solar" (http://sustainablebusiness.com/index.cfm/go/news.display/id/15670). SustainableBusiness.com. 2008-03-27.

Further reading

- Fthenakis, V.; Kim, H. C. (31 May 2007). "CdTe photovoltaics: Life cycle environmental profile and comparisons" (http://www.clca.columbia.edu/papers/CdTe_Photovoltaics_Life_Cycle_Environmental_Profile.pdf) (PDF). *Thin Solid Films*. **515** (15): 5961. Bibcode:2007TSF...515.5961F (https://ui.adsabs.harvard.edu/abs/2007TSF...515.5961F). doi:10.1016/j.tsf.2006.12.138 (https://doi.org/10.1016%2Fj.tsf.2006.12.138).
- Hill, A. H. "Progress in Photovoltaic Energy Conversion" (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19660006117_1966006117.pdf) (PDF). Washington, DC: NASA.
- Stevenson, Richard (August 2008). "First Solar: Quest for the $1 Watt" (http://spectrum.ieee.org/aug08/6464). *IEEE Spectrum*. **45** (8): 26–31. doi:10.1109/mspec.2008.4586284 (https://doi.org/10.1109%2Fmspec.2008.4586284).