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

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Abstract.

Cadmium telluride (CdTe) photovoltaic (PV) technology has recently achieved relatively high power conversion efficiency, low manufacturing cost, combined with durability, and good performance in the high temperature uses. The deployment rate of CdTe PV has grown rapidly in recent years and CdTe PV has the potential to contribute as one of the further scaling-up solar cells. This review evaluates the environmental, health and safety (EHS) of CdTe PV installations throughout their life-cycle, from raw material acquisition, module manufacturing, module use, to end-of-life disposal. The review bases the assessments on the existing scientific literatures on the EHS aspects of CdTe PV modules, including assessment of carbon footprint and energy payback time compared with other renewable energies.

1. Introduction

CdTe PV is a technology which is based on the use of a CdTe/cadmium sulfide (CdS) thin film semiconductor layer for absorption and conversion of solar energy to electricity. CdTe PV's deployment rate has grown more rapidly than conventional silicon solar technologies in recent years (Mehta, 2010). This is due to the fact that CdTe PV has recently achieved relatively high efficiency, low manufacturing cost combined with durability, and good performance in the high temperature uses (Zweibel et al., 2008).

Studies in CdTe technology started in the 1950s, when CdTe was identified as having a proper energy band gap (about 1.5 eV) which almost perfectly matched distribution of photons in the solar spectrum in terms of optimal conversion to electricity (Jenny and Bube, 1954; Goldstein, 1958). 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 CdTe/CdS cell efficiencies were GE in the 1960s, and then Kodak, Monosolar, Matsushita, and AMETEK. In 1999, Solar Cells Incorporated (SCI) became First Solar, which is currently a leading company in the CdTe PV market.

Life cycle assessment (LCA) involves the inventory of material and energy flows in and out of a product, and assessments of their impacts. Previous applications of LCA to PVs focused on determining energy payback time and reductions in carbon-dioxide emissions. Many reports have emphasized the need for further study on the environmental aspects of CdTe PVs, including decommissioning and recycling of end-of-life CdTe modules (Kato et al., 2001). Figure 1 shows life cycle phases of PV modules. In this review, the EHS aspects of CdTe PV systems over their entire life cycle, including extracting refining and purifying raw materials, module manufacturing, module use, and end-of-life disposal, were assessed. General parameters for the life cycle assessment, including carbon footprint and energy payback time, were also reviewed and compared with other renewable energies. Lastly, the EHS practices currently in place at First Solar, one of the leading companies in CdTe PV modules, were reviewed on the basis of a tour of First Solar's Kulim, Malaysia manufacturing and recycling plant, on May 24-25, 2012.

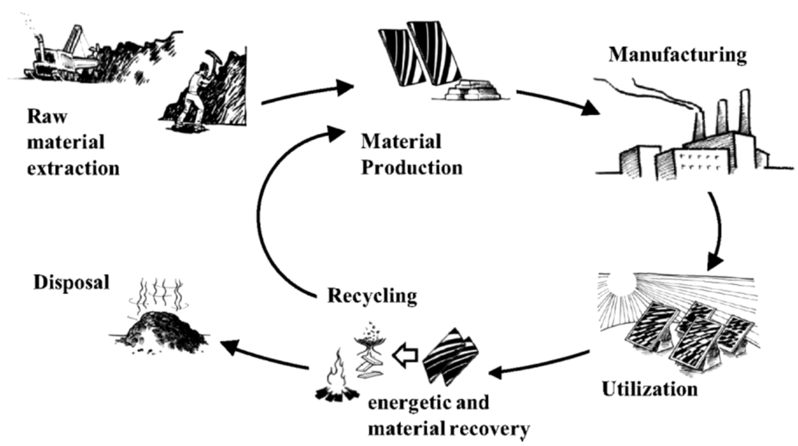

Figure 1. Life cycle phases of photovoltaic modules (Held and Ilg, 2011)

2. Lifecycle EHS Impacts of CdTe PV Systems

2.1 Production of Cd and Te

Cd is used primarily in Ni-Cd batteries and is also used in the control rods of nuclear reactors. Previously, it was used in anticorrosive plating, pigments, and stabilizers, but recently those applications were drastically curtailed. Cd is generated as a byproduct of smelting base metals, i.e., Zn ores, and to a lesser degree Pb ores and Cu ores. If it is not controlled, Cd emissions could be found in those production processes. In most recent years, conventional Zn production uses more advanced hydrometallurgy procedures that drastically reduced Cd emissions (Table 1). Nevertheless, because Zn is generated in very large quantities, more Cd is generated as byproduct than it is consumed annually. The excess can either be put to beneficial uses or be encapsulated and buried, stored for future use, or disposed of in landfills as hazardous waste. Recent study by Matsuno et al. (2012) suggested that there would be a problem due to Cd oversupply in the near future. Arguably, encapsulating cadmium as CdTe in PV modules is an important alternative to its current uses (Fthenakis, 2004; Raugei and Fthenakis, 2010).

Table 1. Cadmium emissions from old and new zinc-production processes (from Fthenakis, 2004).

Process	Cadmium emissions	
	g Cd/ton Zn	(% Cd loss)
Roast/leach/electrowinning process (hydrometallurgy)	0.2	0.008
Roast/blast furnace smelting	50	2
Former roast/blast furnace smelting (not in use any more)	100	4

One of the least understood and the most subtle concerns with CdTe PV is the supply of Te (Zweibel, 2010). Te is an element used in limited applications; outside of PV, Te is mainly used for manufacturing thermoelectric materials, machinable steel and as catalysts for producing synthetic fibers. Therefore, only a small amount of Te is available, with current annual production of approximately 640 metric tons per year (Zweibel, 2010). Most of it comes as a by-product of Cu, with smaller byproduct amounts from Pb and Au. One gigawatt (GW) of CdTe PV modules requires about 91 metric tons of Te (Zweibel, 2010), so this seems like a potentially limiting factor. From a report from International Energy Agency, thin film (CdTe and CIGS) PV market shares through mid-century are expected to be met by currently understood future tellurium and indium availability (Candelise et al., 2011). Some researchers have shown that well-known undersea ridges are rich in Te and by themselves could supply more Te than we could ever use for all of our global energy (Cohen, 1984). However, it is not yet known whether extracting this undersea Te is technically and economically feasible, nor whether there is much more tellurium elsewhere that can be recovered. Fortunately, it was reported recently that there are some sources of Te as a primary ore. Mines in Mexico, China, and Sweden have rich bismuth Te ores, with Te concentrations of almost 20% (Zweibel, 2010). These deposits will allow the economic recovery of Te, independent of the production of Cu, with minor (~1%) increase in the life cycle cumulative energy demand of CdTe PV (Fthenakis and Anctil, 2012). In addition, material availability concerns will be eased with future enhanced recovery during primary production, reductions of the thickness of semiconductor layers, increases in the efficiency and life expectancy of modules, and recycling of end-of-life PV modules (Fthenakis, 2012).

Some emissions could be found in the purification of byproduct Cd and Te to be semiconductor-grade Cd and Te. However, with capture techniques, i.e. high-efficiency particulate air (HEPA) filters, and waste recycling, those emissions are below acceptable levels.

2.2 CdTe Characteristics, Production, and Toxicity

CdTe is a crystalline compound with lattice constant of 0.648 nm (at 300 K), Young's modulus of 52 GPa, and poisson ratio of 0.41. Its thermal conductivity, specific heat capacity, and thermal expansion coefficient are 6.2 $W{\cdot}m/m^2{\cdot}K$, 210 J/kg·K, and 5.9×10^{-6}/K, respectively, at 293K (Palmer, 2008). CdTe has very low solubility in water (Brookhaven National Laboratory and the U.S. Department of Energy, 2003). It can be chemically etched by using many acids, including hydrochloric and hydrobromic acid, forming (toxic) hydrogen telluride gas (Hosokawa *et al.*, 2012) and toxic cadmium salts. It is unstable in air at very high temperatures (boiling point of CdTe is about 1050˚C) (Fthenakis *et al.*, 2005). CdTe for PVs is generally produced from high-purity Cd and Te via proprietary methods. Production is limited and the volumes produced are not published. Reportedly, 100% of the feedstock is used and there are no quantifiable emissions during production of semiconductor-grade CdTe (Fthenakis, 2004).

As a cadmium compound, CdTe is often documented as toxic if ingested, if its dust is inhaled, or if it is handled improperly (i.e. without appropriate personal protective equipment and other safety precautions). Recent toxicological research by Zayed and Philippe (2009) and Kaczmar (2011) described below have differentiated CdTe from other Cd compounds. According to Held et al. (2012), the European Chemicals Agency (ECHA) no longer classified CdTe as harmful if ingested nor harmful in contact with skin. Once properly and securely captured and encapsulated, CdTe used in manufacturing processes may be rendered harmless. CdTe is less toxic than elemental Cd, at least in terms of acute exposure toxicity testing (Zayed and Philippe, 2009).

In evaluating risk from environmental emissions, toxicological data is often read-across from the parent element (Cd) to the compound (CdTe), because of limited specific toxicological data on CdTe. However, recent toxicity studies indicate that this may not be appropriate. CdTe exhibits aqueous solubility and bioavailability properties that are approximately two orders of magnitude lower than the 100% solubility and bioavailability of $CdCl_2$, which means that CdTe does not readily release the reactive ionic form of Cd (Cd^{2+}) upon contact with water or biological fluids. Based on these results, the toxicity and environmental mobility of CdTe would be expected to be much lower than other forms of Cd (Kaczmar, 2011).

Previously, Zayed and Philippe (2009) evaluated acute inhalation and oral toxicities of CdTe in rats and found the median lethal concentration and dose to be orders of magnitude higher than that of Cd. Moreover, prior testing by Harris *et al.* (1994) showed no detectable effects of CdTe on male or female rat reproduction.

Researchers in U.S. have reported that CdTe PV modules appear to be more environmentally friendly than all other current uses of Cd (Fthenakis, 2004). The approach to CdTe safety in EU and China is much more cautious. Cd and Cd compounds are considered as toxic carcinogens in EU, whereas China regulations previously allow some Cd products for export only (Sinha *et al.*, 2008).

For EU, the Restriction on the use of certain Hazardous Substances (RoHS) Directive is an environmental legislation that has been in effect since July 1, 2006 and has been revised in 2011. It deals with six hazardous materials in electrical and electronic equipment (including Cd). The RoHS Directive separates a product into individual parts of homogeneous materials. Each part must not contain the banned substance exceeding a maximum concentration limit. The limit is 1000 ppm (parts per million) for other five materials but only 100 ppm for Cd. In November 2010, the European Parliament, European Commission, and European Council agreed on a revised RoHS Directive (**Directive 2011/65/EU)** under which all electrical and electronic equipment (EEE) are included in the scope of the RoHS directive unless specifically excluded or exempted from coverage. PV panels are explicitly excluded from the scope of RoHS. More specifically, article 2 describes PV panels as follows; photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications (European Commission, 2011).

For China, RoHS has also been applicable recently (Design Chain Associates, 2012). The scope of Chinese RoHS includes a potential labeling and information disclosure requirement (China RoHS 1) and a materials restriction requirement applied to a separately promulgated list of electronic information products (China RoHS 2). China ROHS 2 has not yet been promulgated and is pending the publication of the China RoHS 2 catalogue. Recently some CdTe PV modules have been sold in China.

2.3 CdS and its Characteristics

CdS is an inorganic compound in a yellow solid form. As a compound that is easy to isolate and purify, it is the main source of Cd for various commercial applications (Wiberg and Holleman, 2001). CdS is mainly used as a pigment. CdS and cadmium selenide are used in manufacturing of photoresistors sensitive to visible and near infrared light. In thin-film form, CdS can be combined with other layers for use in thin-film solar cells as the *n*-type material in a *p-n* junction (Zhao *et al.*, 2009). CdS was also one of the first semiconductor materials to be used for thin-film transistors (TFTs) (Weimar, 1962).

The CdS share in the CdTe/CdS PV modules is substantially lower than the CdTe share (Beckmann and Mennenga, 2011.).CdS accounts for less than 3% of the total Cd content in the module. It has even less solubility than CdTe (< 1% solubility), low acute oral and dermal toxicity (classified as non-toxic for acute exposure in material handling requirements for shipping/transportation), and low respirable fraction (less than 10 μm) when used in PV manufacturing, which limits inhalation toxicity.

2.4 CdTe PV Manufacturing

The two leading methods of making CdTe thin films, electrodeposition of CdTe combined with chemical surface deposition of CdS (not commercially used since 2004), and high-rate vapor transport of the two compounds, use Cd compounds very efficiently. There are about 1% loss in the electrodeposition process, and about 10-30% loss in the vapor-transport process. In both processes, the Cd compounds can be collected and recycled or safely disposed of in a secure landfill (Fthenakis, 2004; Smigielski, 2011).

CdTe PV installation workers do not have the possibility of exposure to the semiconductor layer of the module because it is encapsulated between two sheets of glass. The bio-monitoring in the CdTe PV factory shows no Cd release to the workers. Moreover, the reviews of medical monitoring data in First Solar's CdTe PV manufacturing and recycling factories have concluded that the medical surveillance data for blood and urine Cd show no evidence of increased Cd exposure from the workplace. (Akbar 2009).

2.5 CdTe PV Operations

2.5.1 Routine

General. Under normal operation, CdTe PV modules do not pose risk to human health or the environment because the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated with a second sheet of glass. Unless the module is ground to a fine dust, particulate matters cannot be generated. The melting point of CdTe is 1041 °C, and evaporation starts at 1050 °C. Sublimation occurs at lower temperatures, but the vapor pressure of CdTe at 800 °C is only 2.5 torr (0.003 atm) (low vapor pressure). The melting point of CdS is 1750 °C and its vapor pressure due to sublimation is only 0.1 torr at 800 °C. Therefore, it is impossible for any vapors or dust to be emitted when using PV modules under normal conditions (Fthenakis, 2004).

Soil Contamination. Potential health risks from ground-mount CdTe PV installations on agricultural lands were recently evaluated by the Bavarian Agricultural Agency (Ebert and Muller, 2011). Risks from potential leaching were found to be minimal. CdTe has very low solubility in water, and it can only be chemically etched by acids, forming (toxic) hydrogen telluride gas and toxic cadmium salts as mentioned previously. Moreover, in the recycling step, it was found that highly concentrated H_2SO_4 and H_2O_2 were needed to extract Cd and Te (Fthenakis, 2004). It should also be noted that the presence of acid alone cannot etch modules. A module would have to be broken into small (mm-scale) pieces and agitated in acid (similar to the recycling process) in order to dissolve the semiconductor materials. Removal of broken modules from project sites is recommended for precautionary soil protection (Ebert and Muller, 2011). This is consistent with routine inspections and power output monitoring that are used to diagnose broken modules for collection and recycling (Sinha et al., 2012).

Solar Reflection. Diffuse reflectivity or reflecting power of a surface is generally measured by its albedo value. This value refers to a property of a material or surface defined as the total amount of energy reflected divided by the total amount of energy impacting the material or surface. Albedo value of CdTe PV modules is about 0.26 (Markvart and Castalzer, 2003; Donovan, 2010). This value is very close to the values of grass, dry grass, and uncultivated fields, indicating that the CdTe PV does not cause the problem of high solar reflection to the environment.

Table 2. Typical albedo values (Donovan, 2010).

Surface Type	Albedo
Grass	0.25
Dry grass	0.28 - 0.32
Uncultivated fields	0.26
Bare soil	0.17
Asphalt	0.15
Weathered concrete	0.20
Fresh snow	0.80 - 0.90
Water surfaces (solar angle range from 45° to 10°)	0.05 - 0.22

2.5.2 *Accidents*

Some PV stakeholders have raised concerns about the potential exposure to CdTe from non-routine circumstances, such as release during fires and leaching of broken modules.

Broken Modules. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. Fortunately, unless the CdTe PV module is ground to fine dusts recently, dust particles are not generated from PV modules. Steinberger (1997) addressed the potential of Cd leaching out by rain from broken or degraded CdTe modules. He concluded that CdTe releases are unlikely to occur during accidental breakage. The only scenario of potential exposure is if a fire consumes the PV module and releases cadmium from the material into the air. In addition, routine inspections and power output monitoring diagnose broken modules to be removed for collection and recycling (Sinha et al., 2012). A weather event that could potentially damage many modules would also significantly affect electricity production, resulting in detection and removal of broken modules through performance monitoring and inspection.

Fire. Heating experiments to simulate residential fires in glass-CdTe-glass PV modules showed that most of the Cd content was encapsulated in the molten glass matrix. The pathway for some loss of Cd was likely through the perimeter of the modules before the two sheets of glass fused together, which is a very small area. It was estimated that only <0.04% of the Cd content would be emitted during the fires that cover the wide flame temperature zone of 760-1100°C. Multiplying this with the probability of occurrence for residential fires and the probability of sustained fires in utility systems, the emissions of Cd are considered to be essentially zero (Fthenakis *et al.*, 2005).

The distribution calculations for worst-case conditions, assuming a total release of all cadmium inventories showed that a serious danger for the immediate neighborhood and general public can certainly be excluded when CdTe PV modules burn (Beckmann and Mennenga, 2011). Moreover, recent fate and transport evaluations applying conservative assumptions of cadmium exposures from rainwater leaching of broken CdTe PV modules and emissions from a fire concluded that concentrations at the point of exposure would be expected to be below published health-based screening levels (Sinha *et al.*, 2011).

Even though the possibility of sustained fires in utility systems and the Cd content emitted are very low, routine maintenance of the PV system to prevent the fire or any accident should be carried out. Not only Cd, but a tiny percentage of Te was released in the typical residential fire temperature range 760-900°C, but a significant fraction of Te was released at higher temperatures (1000-1100°C) (Fthenakis *et al.*, 2005).

Hailstorm. Strong hailstorms may destroy PV modules, thus justifying a consideration on the case of broken modules. Whether Cd can be released when a module is damaged by hail, it is important to know whether the semiconductor layer, conductors, and solders are exposed to weather conditions. In practice, water could enter through hairline cracks which are likely to develop. International Electrotechnical Commission (IEC) published a standard for the hail impact test (IEC61646, section 10.17). The PV modules which pass this test before placing on the market are secure for hailstorm. With a PV free field plant, it is unlikely to expect the same small fragment size which was used for the batch/elution tests for estimating leaching potential. The front glass of solar modules is hail tested. Moreover, even in case of the breakage of the glass, the laminate protects against pollutant emission. It should be kept in mind that the batch tests for estimating leaching potential can cause a mechanical related abrasion of the CdTe layer which is unlikely to happen in free field plants (Ebert and Muller, 2011). In addition, routine inspections and power output monitoring diagnose broken modules to be removed for collection and recycling (Sinha et al., 2012). A weather event that could potentially damage many modules would also significantly affect electricity production, resulting in detection and removal of broken modules through performance monitoring and inspection.

Flood or Water Submersion. Even though CdTe has very low solubility in water, adequate toxicological and ecotoxicological information, and data on effects of flood or water submersion of broken modules are very important. Current data includes aquatic toxicity testing performed according to OECD and USEPA test guidelines with zebrafish as the recommended test species. There were no effects (lethal or sublethal) from CdTe at aquatic saturation for zebrafish over 96 h (Kaczmar, 2011). In addition, based on long-term transformation and dissolution testing of CdTe, a 1 mg/L loading showed a concentration of 15 µg of Cd/L after 28 d, indicating low (≈1.5%) long-term solubility (Kaczmar, 2011). Note that PV project site selection includes hydrological site surveying and evaluation, which limits the potential for flooding.

2.6 CdTe PV End-of-Life

Because CdTe in PV modules is encapsulated by 2 sheets of glass, even if pieces of modules inadvertently make it to a municipal waste incinerator, cadmium will dissolve in the molten glass and would become part of the solid waste (Fthenakis, 2004). The leachability tests that are used within the EU for Waste Acceptance Criteria (WAC) testing showed that the leaching potential of the modules was small and that the modules, while not acceptable for disposal in an inert landfill, would be acceptable in other classes of landfill as non-hazardous waste (Golder Associates, 2010). Concerning leaching, there are several independent studies of CdTe modules concerning mass concentration test and standard leaching tests commonly used in the European Union that assessed that CdTe PV modules are classified as a non-hazardous waste at the end of their life (Wehrens, 2011; Steinberger, 1998).

According to Thai laws and regulations on waste management (B.E. 2548; Department of Industrial Work, 2005), solar cell modules are classified as an electronic waste (E-waste). This E-waste is in the group of HA (Hazardous Waste - Absolute entry) and HM (Hazardous Waste - Mirror entry). Therefore, end-of-life PV modules have to be analyzed in the laboratory to investigate the hazards before disposal. In addition, considering Annexes I and VIII of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, Cd-containing items are classified as a controlled waste. Hazardous wastes listed as controlled items for transboundary movement are defined in the *Notification of Ministry of Industry on List of Hazardous Substances B.E. 2546 (2003),* issued under the *Hazardous Substance Act. B.E. 2535 (1992).* Therefore, before transporting spent PV modules to the recycling site or to other countries, permission from the Pollution Control Department (PCD) should be obtained and waste management procedures should be in accordance with the Basel Convention (Pollution Control Department, 2009).

Recently, the PV industry is recycling CdTe PV modules at the end of their useful life (First Solar, 2010). Recycling is important to the long-term sustainability of the PV industry for managing large future waste volumes and recovering valuable materials (glass, copper, aluminum, semiconductor materials, back contact metals, *etc.*) for use in new PV modules and other new products. Held (2009) presented the environmental profile of recycling process of spent CdTe PV modules. It showed that the life cycle primary energy demand and carbon footprint of CdTe PV can be significantly reduced through module recycling. In addition, the recovery of Cd and Te will result in further reduction of the life cycle environmental impact of CdTe PV, in addition to providing a source of Te.

3. Emissions from Overall CdTe Life Cycles

The total Cd in CdTe PV has been evaluated on a life cycle basis (Fthenakis, 2004) and found to produce minimal environmental emissions (e.g., air emissions of 0.02-0.3 g Cd/GWh compared to 2-3.1 g Cd/GWh from coal burning power plants; for other PV systems and energy generation options, see Figure 2).

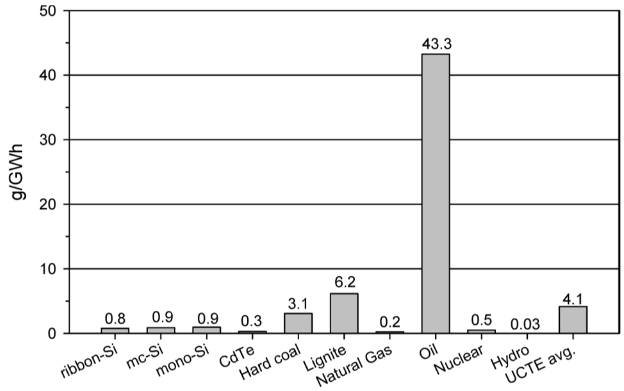

Figure 2. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumptions in comparisons with other electricity generation options (Fthenakis *et al.*, 2008).

Emissions from the life cycle of four major commercial photovoltaic technologies, *i.e.* ribbon-Si, multicrystalline Si (multi- or mc-Si), monocrystalline Si, and thin-film CdTe systems, were quantified (Fthenakis *et al.*, 2008). Replacing grid electricity with central PV systems presents significant environmental benefits, which for CdTe PV amounts to 89-98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species. In fact, life-cycle Cd emissions are even lower in CdTe PV than in crystalline Si PV, because the former use less energy in their life cycle than the latter. More specifically, thin film photovoltaics require less energy in their manufacturing than crystalline Si photovoltaics, and this translates to lower emissions of heavy metals, SO_x, NO_x, PM, and CO_2.

4. Carbon Footprint

CdTe PV provides the lowest carbon footprint of current PV technologies (de Wild-Scholten and Schottler, 2009; de Wild-Scholten, 2011) and almost lowest among other energy alternatives [*i.e.*, carbon footprints of nuclear ~8; wind ~12; CdTe PV ~15; crystalline Si (2006) ~30; poly-Si (hydropower and wafer/cell/module) ~19-34; and coal ~1070 g CO_2-eq/kWh (de Wild-Scholten and Schottler, 2009; de Wild-Scholten, 2011), see Figure 3].

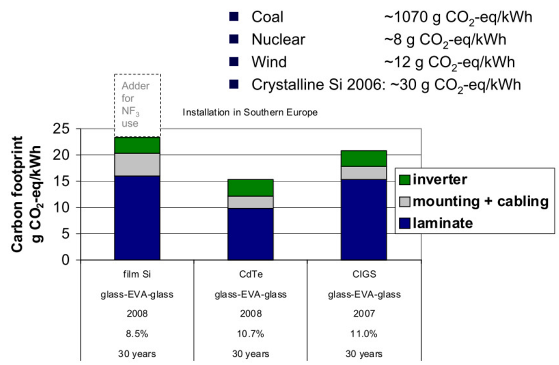

Figure 3. Carbon footprint of various PV systems compared with other electricity generation options (de Wild-Scholten and Schottler, 2009)

5. Energy Payback Time

Energy payback time (EPBT) is defined as the period required for a renewable energy system to generate the same amount of energy that was used to produce, operate, and decommission the system itself (Fthenakis et al., 2011). In order for renewable energy technologies to serve as effective alternatives to fossil fuel based energy, their EPBT must be short. Once the EPBT has passed, the renewable energy technology is a source of green energy that displaces fossil fuels.

CdTe PV provides the fastest energy payback time of current PV technologies, *i.e.*, energy payback times of CdTe PV (2010) ~0.7 years; µm-Si (2012) ~1 year; CIGS PV (2010) ~1.3 years; multicrystalline Si (2009) ~1.6 years; and monocrystalline Si (2008) ~ 1.7 years (de Wild-Scholten, 2011; see Figure 4).

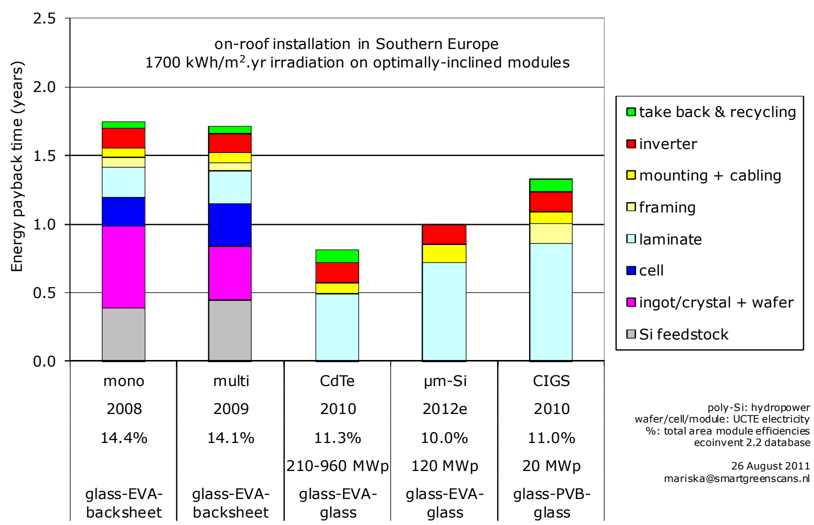

Figure 4. Energy payback time of commercial PV systems installed on roof-top at irradiation of 1700 kWh/m^2/year on optimally-inclined modules. The data for micromorphous silicon PV modules are estimates (de Wild-Scholten, 2011).

6. First Solar's CdTe PV Manufacturing and Recycling EHS Policies and Practices

According to First Solar, low cadmium emissions, small carbon footprint, and short energy payback time are primarily related to state-of-the-art technology and commitment to continuously improve the competitiveness and environmental excellence of its CdTe PV technology.

The module collection and recycling program at First Solar for end-of-life module collection and recycling, which use best available technology, provides high recovery rates for semiconductor material (95%) and glass (90%) (Held, 2009).

No major concerns were identified during this review regarding EHS aspects of First Solar's manufacturing and recycling activities. Over the course of several years, First Solar has developed EHS policies and management systems, and has demonstrated continuous improvement in these areas at its facilities globally. First Solar ensures compliance with its EHS policies and regulatory requirements not only through internal practices, but also through periodic audits by third parties. First Solar takes a proactive risk assessment-based approach to EHS issues and promotes continuous improvements to further reduce risks.

7. Conclusions and Recommendations

CdTe PV is an important thin film PV technology that has grown rapidly in recent years. CdTe PV provides the lowest carbon footprint and fastest energy payback time of current PV technologies and other energy alternatives. In the overall lifecycle of CdTe PV, it is found to produce minimal environmental emissions (e.g., air emissions of 0.02-0.3 g Cd/GWh compared to 2-3.1 g Cd/GWh from coal burning power plants) compared to other PV systems and energy generation options. Replacing grid electricity with central PV systems presents significant environmental benefits, which for CdTe PV amounts to 89-98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species.

The principal EHS concern for CdTe PV is the potential introduction of Cd or other hazardous compounds into the environment. To assess risks, CdTe PV has been evaluated on a life cycle basis with regards to raw material, manufacturing, use, and decommissioning stages with recycling.

Raw Materials

Cd and Te are generated as a byproduct of smelting base metals. Encapsulating Cd in CdTe PV modules is an alternative to its current uses in other applications. There is the potential for a Cd oversupply problem in the near future. CdTe PV systems that use cadmium as a raw material should be considered as one of the solutions for a sustainable use of cadmium. However, on another point of view, the most subtle concern of CdTe PV is the supply of Te, because Te is an element not currently used for many applications. Outside of PV, Te is only used in the manufacturing of thermoelectric materials, machinable steel, and in catalysts for producing synthetic fibers. Therefore, only a small amount of Te is available. One gigawatt of CdTe PV modules would require about 91 metric tons of Te compared with current annual production of approximately 640 metric tons per year, so this seems like a potentially limiting factor. Fortunately, recently there are some sources of Te as a primary ore. Forecasted International Energy Agency thin film PV market shares through mid-century are expected to be met by currently understood future indium and tellurium availability. In addition, material availability concerns will be eased with future enhanced recovery during primary production, reductions of the thickness of semiconductor layers, increases in the efficiency and life expectancy of modules, and recycling of end-of-life modules.

Manufacturing

As a cadmium compound, CdTe is often documented as toxic if ingested, if its dust is inhaled, or if it is handled improperly. Nonetheless, the European Chemicals Agency (ECHA) does not classify CdTe as harmful if ingested nor harmful in contact with skin. With proper EHS practices in PV manufacturing, there is no sign of health risk found in CdTe PV workers.

Use

For CdTe PV modules, under normal operation, the modules do not pose a risk to human health or the environment because the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated with a second sheet of glass. Acids can cause etching of the modules; however, it should be noted that a module would have to broken into small (mm-scale) pieces and agitated in acid (similar to the recycling process) in order to dissolve the semiconductor material. Removal of broken modules from project sites is recommended for precautionary soil protection. This is consistent with routine inspections and power output monitoring that are used to diagnose broken modules for collection and recycling.

In foreseeable accidents, e.g. fire, breakage of CdTe PV modules, the emissions of Cd or Cd compounds have been proven to be negligibly small, because the Cd content would be encapsulated in the molten glass matrix in case of fire, and because of the low solubility of CdTe in case of breakage. The pathway for some Cd loss is likely through the perimeter of the modules before the two sheets of glass fused together, which is a limited area. It is estimated that only <0.04% of the Cd content would be emitted during the fires.

Decommissioning

After uses, CdTe PV modules are classified as a non-hazardous waste in the European Union and as hazardous waste in Thailand. The recycling of CdTe PV modules at the end of their useful life provides high recovery rates for semiconductor material (95%) and glass (90%).

Recommendations

In our opinion, CdTe PV systems are well suited for use in large-scale operations, like solar farms with adequate monitoring and environmental management systems, which can provide significant environmental benefits for reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species. As power systems in general should not be located in high risk areas, CdTe PV systems should not be located close to potentially hazardous facilities to avoid potential risks under extreme conditions or in the events of disaster.

8. References

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