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CdTe photovoltaics: Life cycle environmental profile and comparisons

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Abstract

We discuss the emissions of cadmium throughout all the life stages of CdTe PV modules, from extracting, refining, and purifying the raw materials to producing, using, and disposing or recycling of the modules. Then, we compare these emissions with those in the life cycle of three different types of crystalline Si PV modules. The energy requirement and energy pay back times (EPBT) of CdTe PV modules are considerably shorter than that of crystalline Si modules, although the latter exhibit higher efficiencies. This difference is primarily due to the energy used to process silicon, a fraction of which is derived from fossil fuels, inevitably producing Cd and many other heavy-metal emissions. The lower energy requirement of CdTe PV results in lower emissions of all pollutants, including cadmium.
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Keywords: CdTe PV; Life cycle assessment; Life cycle analysis; Environmental

1. Introduction

The production of energy by burning fossil fuels generates many pollutants and carbon dioxide. Indeed, all anthropogenic means of energy production, including solar electric, generate pollutants when their entire life cycle is taken into account. Life-cycle emissions to the environment result from the use of fossil-fuel-based energy to produce the materials for solar cells, modules, and systems. These emissions differ in different countries, depending on that country's mixture in the electricity grid, and the varying methods of material/fuel processing. The lower the energy payback times (EPBT), that is the time it takes for a PV system to generate energy equal to the amount of energy used in its production, the lower these emissions will be Fthenakis and Alsema [1] reported the latest (2004–2005) status of the EPBT and of greenhouse-gas (GHG) emissions in four different photovoltaic rooftop installations, namely ribbon-Si, multi-crystalline Si, mono-crystalline Si, and CdTe systems. Their corresponding EPBTs, under the average Southern European insolation of 1700 kWh/m^2/yr, were 1.7, 2.2, 2.7 and 1.1 years. Although the EPBT of CdTe PV was much lower than that of the other systems, its electrical-conversion efficiency was the lowest in the group (i.e., 9% for CdTe vs. 11.5 % for ribbon, 13.2% for multi-crystalline Si, and 14% for mono-crystalline Si. The production of poly-silicon is the most energy-consuming stage of the silicon module's life cycle, accounting for about 45% of the total primary energy usage during the multi-Si module's life cycle, while electricity demand during the deposition of the CdTe film accounts for its greatest primary energy use during its lifetime [2–4].

2. The life cycle of cadmium in CdTe PV modules

Fthenakis [5] describes the cadmium (Cd) material flows and emissions for the entire stages of the cadmium telluride (CdTe) PV life cycle. This starts with the extraction of Cd and Te. Cd is generated as a byproduct of smelting zinc (Zn) ores (~80%) and lead (Pb) ores (~20%). The Cd content of the Zn concentrate is 0.3–0.5%, and 90–98% of the Cd present in ores is recovered in the mining and beneficiation stages, the rest being contained in mine tailings. Cadmium is recovered from waste streams during the production of zinc, specifically cadmium residues from leaching/electrolytic zinc production, and the particulates from roaster furnaces, which collect in the electrostatic precipitators or bag-houses. Cadmium also is recovered from the particulates collected from lead-smelting operations.

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Table 1
Atmospheric Cd emissions during the life cycle of CdTe PV module

	Air emissions (g Cd/ton Cd[a])	Allocation (%)	Air emissions (g Cd/ton Cd[a])	mg Cd/ GWh[b]
Mining of Zn ores	2.7	0.58	0.016	0.02
Zn smelting/refining	40	0.58	0.23	0.3
Cd purification	6	100	6	9.1
CdTe production	6	100	6	9.1
PV manufacturing	3	100	3	4.5
Operation	0.3	100	0.3	0.3
Disposal/recycling	0	100	0	0
Total				23.3

[a] Ton of Cd used in manufacturing.
[b] Assuming average U.S. insolation (i.e., 1700 kWh/m2-yr), 9% electrical conversion efficiency, and a 30-year life for the modules.

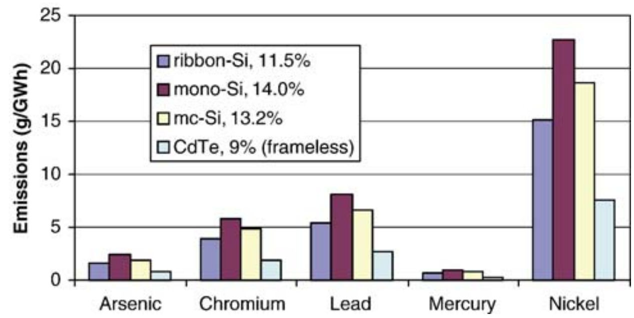

Fig. 2. Emissions of heavy metals due to electricity use, based on European UCTE averages (Ecoinvent database).

These various Cd residues from the Zn and Pb operations are processed to remove impurities. Cd sponge from the Zn smelter (99.5%) is oxidized, and then impurities in the CdO are leached with a spent Cd electrolytic solution and sulfuric acid. Finally, Cd cathodes are removed, melted, and cast. Cd also is produced from the emissions of fumes and dust from lead smeltering that are reacted with sulfuric acid. Calcined cadmium sulfate and impurities are roasted and leached with water to dissolve Cd. Cadmium sulfate is filtered and purified by electrolytic separation.

Tellurium is recovered by leaching the slimes containing Cu, Te, and other elements, which are generated during the electrolytic refining of copper, with dilute sulfuric acid. After cementation with copper, CuTe is leached with caustic soda to produce a sodium telluride solution that is employed as the feed for Te and TeO_2. Additional leaching and vacuum-distillation follows, particularly for obtaining semiconductor-grade (>99.99%) Cd- and Te-powders. The cadmium emissions from zinc-processing operations are allocated between zinc, cadmium, and other byproducts according to the ISO's guidelines. One hundred percent of emissions during the purification of Cd are allocated to Cd (Table 1).

Fthenakis and Kim [4] undertook detailed analyses of emissions during the commercial production of CdTe PV modules. The data used were obtained from First Solar's 25-MW production plant in Perrysburg, Ohio that produces frameless, double-glass, CdTe modules of 1.2 m by 0.6 m, rated at 9% photon-to-electricity conversion efficiency (2004–2005 vintage). Vapor transport deposition (VTD) is the technology used to deposit the semiconductors, which relies on the sublimation of the powders and condensation of the vapors on glass substrates [6]. HEPA filters in the process exhaust have a verified efficiency of 99.97% in collecting submicron-sized particulates from deposition-, laser scribing-, and maintenance-operations. The facility also uses a considerable amount of energy (i.e., 1200 MJp per m^2 of module) that is associated with Cd and other emissions due to the fossil energy used upstream of the production line.

Operating any kind of photovoltaics does not produce any emissions. However, they could be generated during accidental fires on residential roofs. At Brookhaven National Laboratory (BNL) we investigated experimentally the effect of fire on glass-to-glass CdTe PV modules [7]. With the aid of high-energy synchrotron X-ray microprobes, we demonstrated CdTe is effectively contained in the molten glass, under flame temperatures of 760–1100 °C. Only 0.4–0.6% of the Cd content was released through the open perimeter of the modules before the two sheets of glass fused.

BNL and First Solar together developed a hydrometallurgical process for recycling Cd, Te, and glass from CdTe modules. Since all the process stages are conducted at ambient temperature and pressure, no gaseous emissions of Cd are generated during this process [8,9].

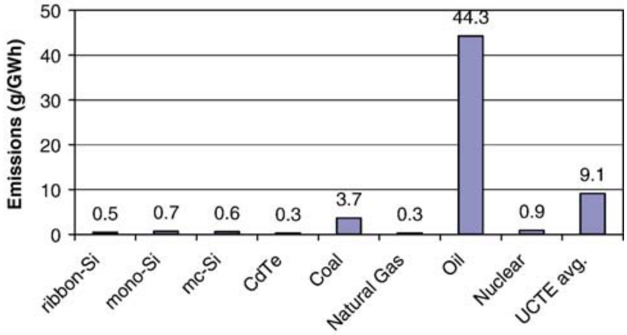

Fig. 1. Life-cycle atmospheric Cd emissions for PV systems normalized for Southern Europe's average insolation of 1700 kWh/m^2/yr, performance ratio of 80%, and lifetime of 30 years. Each PV system is assumed to include a ground-mount BOS as described by Mason et al. [11].

Table 2
Pollution prevented by CdTe PV module for each GWh of electricity generated compared with UCTE grid mixture (Insolation = 1700 kWh/m^2/yr, PR = 0.8, lifetime = 30 years)

	Emission reduction	Unit	Percentage
GHG	459	t CO_2-eq.	95
NO_x	0.8	t	95
SO_2	1.8	t	97
Arsenic	30	g	97
Cadmium	8.9	g	97
Chromium	74	g	97
Lead	103	g	97
Mercury	13	g	97
Nickel	289	g	97
Thorium-230	8	kBq	98
Uranium-238	35	kBq	98

Table 1 gives the air emissions of Cd during the various stages of the life of CdTe PV, compiled from reference [5] and adjusted for European solar irradiation conditions.

3. Emissions of cadmium & other heavy metal during the operation of fossil-fuel power plants

Coal and oil-fired power plants routinely generate Cd during operation, in contrast to photovoltaics, which do not generate emissions during its normal use. According to data from the US Electric Power Research Institute (EPRI), under the best/optimized operational and maintenance conditions, burning coal for electricity releases into the air between 2 to 7 g of Cd/GWh (assuming well-maintained electrostatic precipitators or baghouses, and an average concentration of Cd in US coal of 0.5–1.5 ppm) [10]. In addition, 140 g/GWh of Cd inevitably collects as fine dust in boilers, baghouses, and ESPs. Furthermore, a typical US coal-power plant emits per GWh about 1000 t of CO2, 8 t of SO2, 3 t of NOx, and 0.4 t of particulates. The emissions of Cd from heavy-oil burning power plants are 12–14 times higher than those from coal plants, although heavy oil contains much less Cd than coal (~0.1 ppm), because these plants do not have particulate-control equipment. Cadmium emissions are also associated with natural gas and nuclear fuel life-cycles because of the energy used in the associated fuel processing and materials productions.

4. Comparisons of life-cycle cadmium emissions in the life-cycles of four types of PV modules

The production of energy inevitably generates toxic- and greenhouse gas-emissions and the less energy is used in the life-cycle of a product, the lower these emissions will be. Thus, the differences in the energy requirements, especially electricity requirements, between the four types of PV systems described in the introduction above, are directly related to different levels of emissions. The electricity demand for each PV module system, including a common balance of system (BOS), was estimated by tracing the materials and energy networks. Electricity accounted to 71–76% of the total life-cycle primary energy in all the four PV types we examined. Then, emissions of Cd and other heavy metals (e.g., As, Cr, Pb, Hg and Ni) were compiled, based on established emission factors in the average European grid, (i.e., Union for the Co-ordination of Transmission of Electricity, UCTE). The composition of the UCTE is fossil fuel—50%, nuclear—34%, hydroelectric—15%, and other—1%.

Fig. 1 shows the Cd emissions in the life-cycles of the four PV modules, and those from coal-, oil-, natural gas-, nuclear-, and average electricity-production. The direct Cd emissions during the life-cycle of CdTe PV modules (i.e., 23 mg/GWh) are much smaller than those from generating the electricity used in producing these same modules (i.e., 234 mg/GWh).

Thus, when CdTe PV displaces coal, it displaces 3.4 g of Cd emissions per GWh produced, and likewise, for heavy-oil, it displaces 44.0 g Cd/GWh. In general, every GWh of electricity generated by CdTe PV modules can prevent 8.8 g of Cd air emissions if used in place of UCTE electricity.

Other heavy-metal emissions associated with the life-cycle electricity usage of the four types of PV systems are shown in Fig. 2. The emission factors are the products of electricity usage during the life cycle of PV modules and the electricity-emission factors from the Ecoinvent LCA database [12]. It shows that, among them, the lower energy payback time of CdTe PV technology results in consistently lower emissions of all air pollutants.

In general, electricity from PV presents great environmental benefits when replacing electricity from the grid. This is equally true for cadmium as for other pollutants. Actually, the common metric of GHG emissions, CO_2-equivalent, is a good yardstick for evaluating the comparative production of other pollutants associated with this method of generating electricity. For each g of CO_2 emitted in energy production, 0.03 μg As, 0.01 μg of Cd, 0.09 μg of Cr, 0.1 μg of Pb, and 0.01 μg of Hg are also emitted. After accounting for the emissions associated with their respective life-cycles, CdTe PV systems reduce 95% to 98% of these emissions (Table 2).

5. Conclusion

Indirect emissions of Cd due to energy used in the life of CdTe PV systems are much greater than the direct emissions. CdTe PV systems require less energy input in their production than other commercial PV systems, and less energy translates to lower emissions of heavy metals (including Cd), as well as SO_2, NOx, PM, and CO_2 in the CdTe cycle than in the cycles of other commercial PV technologies.

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