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Energy Use and Greenhouse Gas Emissions in the Life Cycle of Thin Film CdTe Photovoltaics

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ABSTRACT
The life cycle of the thin film CdTe PV modules in the U.S. have been investigated based on actual production materials and energy inventories and recorded performance data.

INTRODUCTION

With a growing public interest in renewable energy sources, significant attention is paid to the life cycle analysis (LCA) of photovoltaic (PV) devices. Thin film cadmium telluride (CdTe) modules are one of the most promising new, thin-film PV technologies. In its early stage of commercialization, the life cycle environmental performance of a CdTe solar cell is relatively unknown, as the life cycle energy use and emission data on the production stage of cell materials as Cd and Te are scarce and new, advanced vapor deposition processes have prevailed [1].

Early studies indicate that manufacturing of CdTe modules would require 3-4 times less primary energy per m^2 than crystalline silicon modules and comparable energy to thin film amorphous silicon modules [2-4]. However, these studies have evaluated the life cycle energy associated with CdTe PV based on either conceptual manufacturing process or pilot phase manufacturing operation [5] for materials and energy data. The current LCA study is based on a complete set of detailed data from a 25 MW/yr production unit, and actual performance data.

BACKGROUND AND METHOD

The data used in this study were obtained from First Solar's 25-MW production capacity in Perrysburg, Ohio. The facility currently produces frameless CdTe modules of dimensions 1.2 m by 0.6 m, rated at 9% photon-to-electricity conversion efficiency. The technology used to deposit the semiconductors in this facility is vapor transport deposition (VTD), which relies on sublimation of the powders and condensation of the vapors on glass substrates [6,7].

We use the ISO-LCA framework as the primary method for compiling the life cycle inventory and measuring the life cycle impact of associated stages [8]. We also used the Economic Input-Output Life Cycle Assessment (EIO-LCA) method [9] for cross-referencing and to supplement the ISO-LCA analysis. The studied CdTe photovoltaic life cycle stages include materials production, materials transportation and module manufacturing. On-site wastewater treatment is incorporated into module manufacturing and those impacts are included in the module manufacturing stage. The installation, operation and decommissioning of the Balance of Systems (BOS) has been previously investigated [10] and the associated environmental impacts are added to those of the PV modules. Impacts from the capital equipment to produce CdTe modules are not investigated. Those values could vary depending on production capacity and equipment life-time, and are typically absent from this type of analysis. Therefore, the scope of this study would sufficiently serve for comparing the life cycle energy and emissions of CdTe

PV with other types of PV and other energy generation technologies. The inventory data for the CdTe module manufacturing was collected during the first half of 2005 for about 700 items of components and energy usages. The suppliers of those components as well as the CdTe module manufacturing plant are located in the US.

Emissions and energy data associated with materials processing and manufacturing were obtained directly from the module manufacturer and the material suppliers. When such data were not directly available, commercial databases were used. The LCA software 'Simapro' was used for compiling life cycle inventories, calculating aggregated materials usages, and determining life cycle impact metrics.

1. Materials Production

In this stage, the LCI was compiled of the solar cell and photovoltaic module materials (e.g., semiconductors, substrate glass, cover glass, encapsulation, wires, and contacts) (Figure 1). The cell materials include cadmium telluride (CdTe), cadmium sulfide (CdS) and contact metals. The life cycle energy and emissions for producing Cd and Te from concentrates, purifying Cd and Te, and synthesizing CdTe were provided from the material supplier. All the module components other than the cell materials (glass, EVA, wires, tapes, cords, and containers) are categorized as "encapsulation"; these components comprise more than 90% of the module materials.

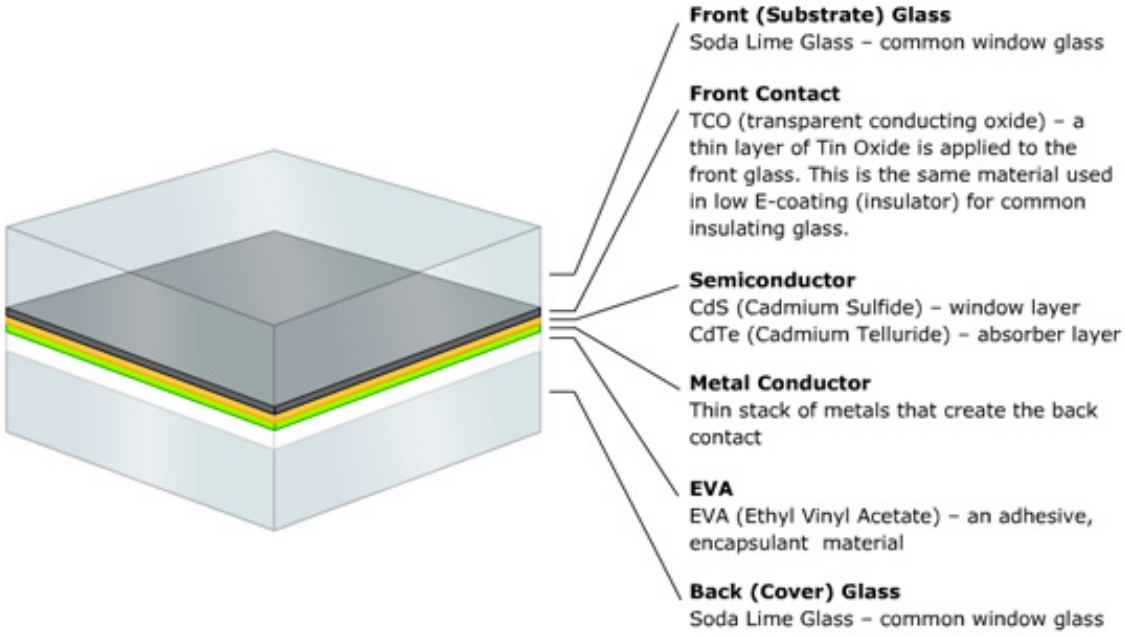

Figure1: Schematic of CdTe module (www.firstsolar.com)

2. Module Manufacturing

<u>Electricity</u> - Electricity demand is the most significant energy usage during the module manufacturing. Module processing, overhead operations, and office use are the main contributors to electricity demand. Module processing includes film deposition, etching, cleaning, and module assembly while overhead operations include environmental control, lightening, health, and safety control.

Chemicals – Chemicals are used during the manufacturing process for cleaning, etching, and waste treatment during operations and maintenance; these include sulfuric acid, nitric acid, isopropyl alcohol, sodium hydroxide, and glass cleaners.
Consumables – Consumables used in the CdTe manufacturing facility include production supplies, repair and maintenance supplies, and safety supplies. Major production supplies include wires, welding rods, and filters while repair and maintenance supplies include cables, cable ties, bolts, nuts, screws, and washers. Safety supplies include goggles, protection gears, and gloves. Around 400 consumable items are included in our analysis.
Office Supplies – Office supplies which include stationeries and computer supplies are difficult to weigh and to analyze material compositions. Therefore, the Environmental Input and Output LCA (EIO-LCA) method was used to quantify their potential environmental impacts. One hundred fifty office supply items were documented and included in this analysis.
Water Use – Water use during the manufacturing process is mainly for glass/substrate/module cleaning with small amounts for chemical solutions and laboratory uses.

3. Transportation

Fuel consumption in the transportation of materials from material supplies to the manufacturing plant, was determined from the actual distance between each location of material or part supplier and the manufacturing plant along with the weights of materials and parts delivered.

LIFE CYCLE MATERIALS AND ENERGY USAGE

Table 1 provides a simplified life cycle material and energy usage to produce one m^2 of CdTe module on the basis of a 9% conversion efficiency. This inventory is compiled during 6 month of actual operation. Some stages of operation, for example, cell deposition have not been optimized yet. Therefore, electricity usages as well as cell material usage in Table 1 may decrease in the future when a more efficient processes or equipment are used.

Table 1: Simplified life cycle material and energy use per m^2 of CdTe modules

Life Cycle Stage	*Input materials, parts, and energy*	*Amount*
Materials Production	Cell Materials (CdTe, CdS, $CdCl_2$, other)	0.065 kg
	Encapsulation (glass, EVA, other)	21.8 kg
Module Manufacturing	Chemicals (acids, cleaning agents)	0.85 kg
	Consumables (safety/maintenance hardware)	0.22 kg
	Water	300 kg
	Electricity (processing)	52.6 kWh
	Electricity (overhead)	4.9 kWh
	Electricity (office use)	1.1 kWh
	Office Supplies	$ 0.37
Transportation	Distillate Fuel Oil	0.15 L

LIFE CYCLE IMPACT METRICS

Life cycle impact metrics were investigated with the LCA software "Simapro". Commercial databases (e.g., Franklin, U.S. Input-Output, Ecoinvent and ETH-ESU) were used to calculate emissions and energy consumptions that were not provided by suppliers [9-11]. The results are tabulated in Table 2.

Table 2: Basic Life Cycle Impact Metrics (based on 9% of cell efficiency, 1800 kWh/m^2/yr of solar irradiation, and 30 years lifetime)

Metric	*Amount*
Primary Energy	1200 MJ/m^2
Energy Payback Time	0.75 years
GHG emissions*	18 g CO_2-eq. /kWh

*100 years of integrated time horizon

Life Cycle Energy and Energy Payback Time

The life cycle energy demand is determined from the LCI in Table 1 along with the materials and energy databases in Simapro. The life cycle energy from each stage is converted from thermal, electrical, and feedstock energy to primary energy according to the conversion efficiencies described in those materials and energy databases, and then aggregated across stages into one number. The materials production stage (cell materials, encapsulation) accounts for 35%, the module manufacturing stage (electricity, consumables, chemicals, and office supplies) 64%, and the transportation stage 1% of the life cycle primary energy demand respectively (Figure 3). The electricity demand during the CdTe film deposition accounts for the greatest primary energy use (84%) during the module manufacturing stage, while encapsulation materials including glass and EVA, dominate the energy requirement (94%) during the materials production stage.

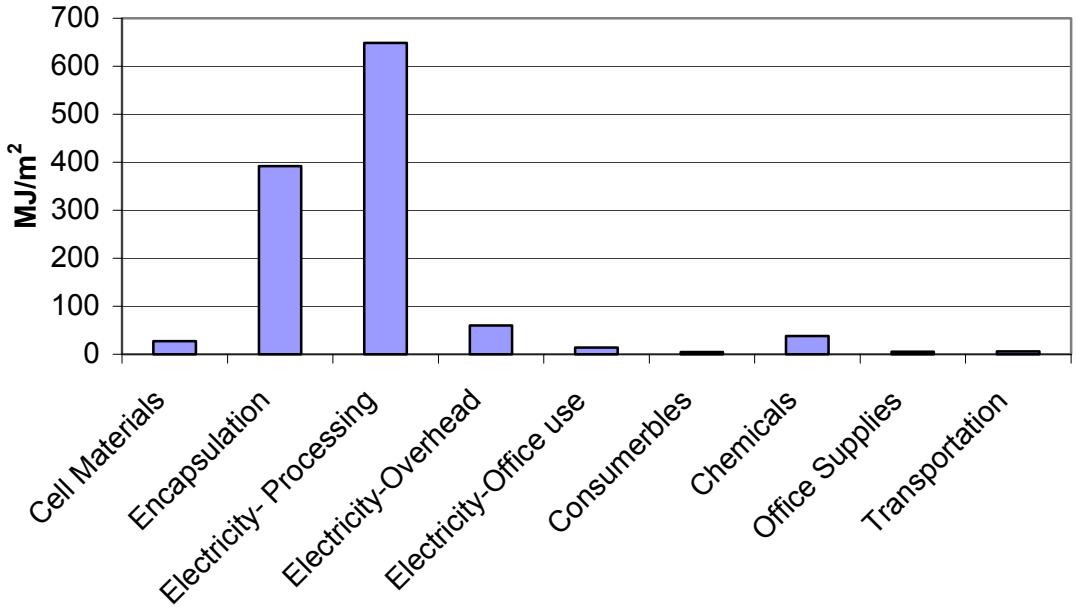

Figure 3: Breakdown of life cycle energy demand during the materials production, manufacturing, and transportation stages of the CdTe life cycle.

The energy payback time is defined as the time period required for a PV system to generate the same amount of energy (either primary or kWh equivalent) used to produce the PV system.
Energy Payback Time (EPBT) = $(E_{mat}+E_{manuf}+E_{trans}) / E_{annual}$
Where,

E_{mat} : Primary energy required to produce materials comprising CdTe PV module
E_{manuf} : Primary energy required to manufacture CdTe PV module
E_{trans}: Primary energy required to transport materials for producing and manufacturing
E_{annual} : Annual electricity generation in primary energy units

With a typical system efficiency of 80%, a one m^2 of CdTe module, which requires 1200 MJ of primary energy to produce, generates 130 kWh/yr of electricity. This translates into 0.75 years of energy payback time by applying the average US electricity conversion efficiency of 0.29 [11]. By adding the EPBT of the Balance of System for a recent central-plant installation [10], we obtained 1.2 years for a ground-mounted, grid-connected system under average U.S. insolation conditions. This estimates accounts for the lower rated efficiency of the CdTe modules than the rated efficiency of the c-Si modules used in the BOS study [10] (9% vs. 12.2%).

Greenhouse Gas Emissions

The greenhouse gas (GHG) emissions emitted during the studied life cycle stages are measured as an equivalent of CO_2 using an integrated time horizon of 100 years. IPCC characterization factors for the direct global warming potential of air emissions are the basis of this calculation [12]. Major emissions considered for the GHG emissions evaluation include CO_2, CH_4, N_2O, and chlorofluorocarbons.

Our estimate of 18 g CO_2-eq. for the CdTe life cycle stages investigated (Table 2) is a significant improvement compared with crystalline Si modules which currently dominate rooftop applications [5, 12, 13]. Adding to this estimated GHG emissions, the emissions attributed to a central (utility) BOS [10], the life cycle GHG emissions fro average U.S. conditions would be 24 g CO_2-eq. This estimate is significantly lower than the GHG emissions from the grid-connected, rooftop mounted crystalline silicon PV life cycles [14]. The GHG emissions from the CdTe fuel cycle determined in this study is comparable to other renewable energy fuel cycles like biomass (~20 g CO_2-eq./kWh) and wind (8-66 g CO_2-eq./kWh) [11, 12, 15].

Uncertainty Analysis

We investigated the uncertainty of the current GHG estimates, in view of limited data on energy and emissions databases for some materials produced in the U.S. In particular, the selection of a database for the flat glasses (substrate and back glasses) used in the CdTe module presented the most important uncertainty in quantifying GHG emissions. Using the ETH-ESU database to determine GHG emissions in the production of these glasses results to 19.3 g CO_2-eq./kWh, while using the Ecoinvent database results to 16.8 g CO_2-eq./kWh [12]. Our reference estimate is based on the average of the two numbers, which is 18 g CO_2-eq./kWh. This choice could be justified from the following reasons. First, the US GHG emissions estimate in Franklin database for similar packaging glasses is in between the estimates for packing glasses from those two European databases. Second, the majority (~60%) of the energy for the glass production is

from natural gas, indicating rather insignificant dependence of GHG estimates on the grid mix of electricity supply [11,12].

CONCLUSION

In this study major life cycle metrics have been investigated for the materials production, manufacturing, and transportation stages of thin film CdTe photovoltaics. This paper presents a snapshot of ongoing efforts to optimize the manufacturing process and the first investigation into the CdTe system based on materials and energy data from a real, mass-production (25 MW_p) plant. The energy payback time of the studied system is 0.75 years and the life cycle GHG emissions factor is 18 g CO_2-eq./kWh using a conversion efficiency of 9%, the US average solar radiation of 1800 kWh/m^2/yr, a lifetime of 30 years, and a system efficiency of 80%. These figures represent a life-cycle environmental advantage over current crystalline silicon PV modules cells. If combined with the state-of-the-art BOS for a central (utility) system, the energy payback time and GHG emissions for the CdTe PV fuel cycle under study would be 1.2 years and 23.6 g CO_2-eq./kWh, respectively. As the current CdTe production line is still being evolved towards an energy optimization, more progress is expected in the energy and emission factors. Further investigation on the CdTe recycling stage is in progress.

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