Life Cycle Water Usage in CdTe Photovoltaics

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***Abstract* — Life cycle water withdrawal for cadmium telluride photovoltaics (CdTe PV) ranges from approximately 382-425 L/MWh, with only ~12% from direct on-site usage. The remainder is related to indirect water withdrawal from the use of grid electricity and raw materials throughout the product life cycle. Approximately half of life cycle water withdrawal is associated with module manufacturing, one-third from balance of systems (BOS), and the remainder from takeback and recycling. Primary contributors to life cycle water withdrawal are use of grid electricity, glass, and on-site water during manufacturing; steel, copper, inverters, and on-site water in the balance of systems; and electricity, chemical use, and transport during takeback and recycling. During manufacturing, water consumption is approximately one-quarter of withdrawal and is due to cooling tower water evaporation and site irrigation. When deployed in the U.S. Southwest, a CdTe PV array can provide net displacement of life cycle water withdrawal of over 1,700-5,600 L/MWh relative to grid electricity.**

***Index Terms* — Water resources, Environmental management, Thin Film PV Modules and Manufacturing**

I. INTRODUCTION

While energy security and climate change have been important market drivers for renewable energy adoption, water security provides an additional driver. For example in the United States, thermoelectric power plants have recently accounted for over 40% of total freshwater withdrawals, even more than for agriculture (Table 1). This energy-water nexus associated with traditional energy sources can be a potential concern, particularly in water-stressed regions.

TABLE I

U.S. WATER WITHDRAWAL BY CATEGORY [1].

Thermoelectric power	49%
Irrigation	31%
Public Supply	11%
Industrial	4%
Other	5%

Because solar photovoltaics (PV) use little to no water during operation (0-19 L/MWh) [2] [3], they provide a potential path forward for addressing the energy-water nexus. However, water is used on-site during PV module manufacturing, project construction, and end-of-life recycling. There is also indirect water usage from the use of grid electricity and raw materials throughout the product life cycle [4].

The purpose of this evaluation is to examine water usage for a specific PV technology, CdTe PV, by life cycle stage, and in relation to other electricity generation sources. For the module manufacturing life cycle stage, a water balance is presented to identify how water is consumed before it is treated and discharged. The net quantity of water avoided by deploying a utility-scale CdTe PV array in the U.S. Southwest is also considered.

II. METHODS

Water usage can be more specifically described with the terms, withdrawal and consumption. Water withdrawal is the amount of water removed from all sources (surface, ground, rain, tap water, etc.) Water consumption is the amount of water evaporated, incorporated into products, or otherwise removed from the immediate water environment. Water consumption is derived from water withdrawal minus water discharge.

2010 life cycle inventory (LCI) data for module manufacturing were obtained from First Solar's plants in Perrysburg, Ohio (U.S.), Frankfurt-Oder, Germany, and Kulim, Malaysia. Global average data was obtained by weighting data across plants based on 2010 module production. Note that the module manufacturing inventory data has also been submitted for inclusion in the Ecoinvent (V.3) database in 2012. LCI data for BOS were obtained from First Solar's planned 550 MWac Topaz Solar Farm in San Luis Obispo County, California [5]. LCI data for end-of-life module takeback and recycling was based on First Solar's U.S. facility in Perrysburg, Ohio (Held, 2009 [6] adapted to U.S. grid electricity). The U.S. facility was chosen for recycling as it would be the recipient of end-of-life modules from a U.S. project. However, recycling operations are consistent across the First Solar plants. Key life cycle inventory parameters are summarized in Table 2.

Life cycle assessment (LCA) of this data has been conducted with Simapro (V. 7.3.2) software and Ecoinvent (V. 2.2) unit processes. Water withdrawal estimates are based on all Simapro raw material water categories (groundwater, lake, river, ocean, salt, cooling, unspecified, etc.) excluding water used in running hydroelectric turbines (turbine use). The latter is excluded because water withdrawals typically represent off-stream use (water removed from the natural body), whereas turbine use represents in-stream use (use of water in the natural water body) [7].

LCA water impacts per MWh energy output follow IEA Task 12 LCA methodology guidelines [8] and are based on Q4 2011 average module conversion efficiency of 12.2%. Project-specific data on performance ratio (0.812), plane of array irradiance (2199 kWh/m^2/yr), and module degradation rate (0.70%/yr) have been obtained in the fourth quarter of 2011 from First Solar's performance engineer utilizing PVsyst V. 5.52 software (C. Schwartz, personal communication). For modules, a 30 year lifetime is evaluated, and for BOS mounting structures, a range of 30-60 year lifetime is evaluated.

Water withdrawal displaced by deploying a CdTe PV array in the U.S. Southwest is based on the mix of electricity generation sources in the California grid (USEPA CAMX eGrid subregion) [9]. These generation sources in combination with LCA water withdrawal estimates by generation source [4] are used to estimate net water withdrawal avoided (L/MWh) by a CdTe PV array (Eq. 1).

$$ND = \left(\sum_{GS} f_{GS} \times WW_{GS} \right) - WW_{CdTePV} \qquad (1)$$

where:
ND = net displacement of water withdrawal (L/MWh)
GS = generation source
f_{GS} = fractional contribution of generation source to California grid
WW_{GS} = life cycle water withdrawal per generation source (L/MWh)
WW_{CdTePV} = life cycle water withdrawal by CdTe PV (L/MWh)

TABLE II
KEY LIFE CYCLE INVENTORY PARAMETERS CORRESPONDING TO FIGURE 1

				Pedigree Matrix[a]					
Life Cycle Stage	Parameter	Value	Unit per m^2 module	Reli-ability	Comple-teness	Temp-oral Corr-elation	Geog-raphic Corr-elation	Techno-logical Corr-elation	Sample Size
Module (weighted average across U.S., German, and Malaysian facilities)	Electricity	29.7	kWh	1	1	1	1	1	3
	Solar Glass	8.39	kg	1	1	1	1	1	3
	Glass Tempering	8.39	kg	1	1	1	1	1	3
	Flat Glass	8.15	kg	1	1	1	1	1	3
	Tap water (from utility bills)	182.8	kg	1	1	1	1	1	3
BOS (from Topaz Solar Farm, Cali-fornia)	Steel, low-alloyed	10.2	kg	2	4	1	1	1	3
	Zinc coating	0.63	m2	2	4	1	1	1	3
	Tap water [5]	89.1	kg	2	4	1	1	1	3
	Inverter, 500 kW	0.00022	-	2	4	1	1	1	3
	Copper	0.88	kg	2	4	1	1	1	3
Takeback and Recycling (from U.S. facility)	Electricity	4.38	kWh	2	4	1	1	1	3
	Hydrogen peroxide, 50% in water	0.57	kg	2	4	1	1	1	3
	Transport, van <3.5 tonne	1.62	tonne-km	2	4	1	1	1	3
	Transport, lorry >16 tonne	8.67	tonne-km	2	4	1	1	1	3
	Water, deionized (from instrument readings)	5.42	kg	2	4	1	1	1	3

[a]Pedigree matrix characterizes uncertainty in life cycle inventory parameters with lower factors indicating lower degree of uncertainty [10].

III. RESULTS

Table 3 shows LCA water withdrawal across the life cycle stages of CdTe PV. Approximately half of life cycle water withdrawal is associated with module manufacturing, one-third from BOS, and the remainder from takeback and recycling. The direct (on-site) withdrawal of water is a small (~12%) percentage of total LCA water withdrawal. In the module manufacturing life cycle stage, the major contributors to water withdrawal are grid electricity, glass, and on-site water (primarily for module manufacturing, cooling tower, and site irrigation). Steel, copper, inverters, and on-site water (primarily for site preparation and dust suppression during construction) are important to the BOS stage. During takeback and recycling, electricity, chemical use (hydrogen peroxide), and transport are also important contributors to life cycle water withdrawal (Fig. 1).

Direct water withdrawal for module cleaning during PV operation is not shown in Figure 1 because, in general, First Solar does not recommend module cleaning in its project sites. An exception is in the Middle East region where a brush cleaning method has been developed that uses no water. For PV in general, module cleaning during operation can result in up to 19 L/MWh of water withdrawal [3].

It should be noted that direct water use in the BOS stage varies by location. For example, First Solar's Desert Sunlight project is also a 550 MWac project. Located in the Mojave Desert region of California, direct water use during construction for dust suppression and site preparation is approximately twice the amount assumed here for the Topaz Solar Farm, which is located in the less arid Carissa Plains of California. Accounting for this variability would increase direct water withdrawal from ~12% to ~15% of total LCA water withdrawal.

TABLE III
DIRECT AND TOTAL LIFE CYCLE WATER WITHDRAWAL (L/MWH) FOR CDTE PV.

Life Cycle Stage	Direct (on-site)	Total
Module	31	224
BOS[a]	15	106-150
Takeback and Recycling	1	51
Total	47	382-425

[a]Variability in total water withdrawal in the BOS stage reflects the 30-60 year lifetime evaluated for BOS mounting structures. Direct water withdrawal in the BOS stage is for dust suppression, which can vary to up to 30 L/MWh based on the aridity of the project site. The value of 15 L/MWh shown here reflects the Topaz Solar Farm in the Carissa Plains of California.

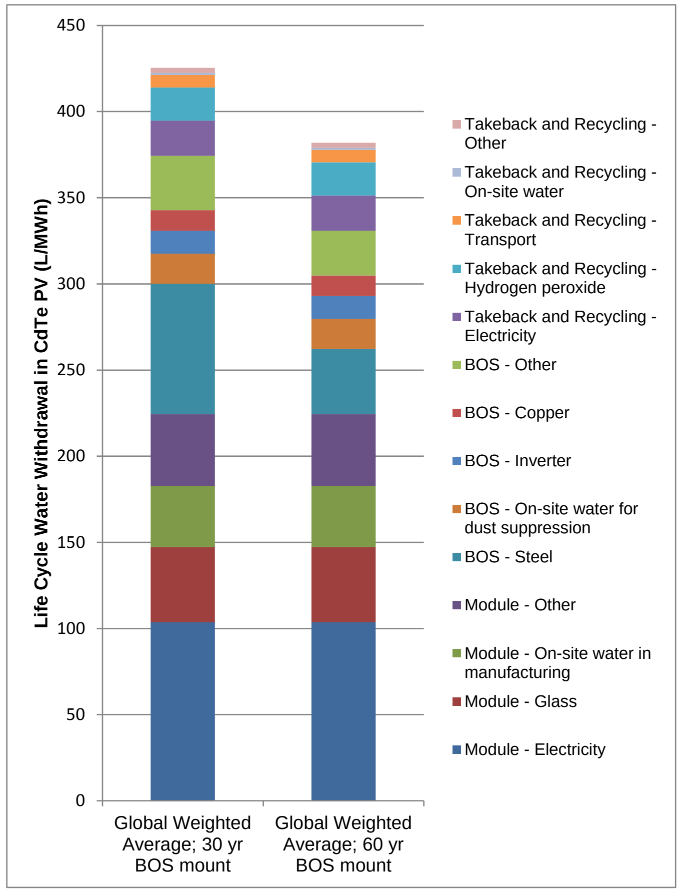

Fig. 1. Major contributors to life cycle water withdrawal in CdTe PV.

The net water withdrawal displaced by deploying a CdTe PV array in the U.S. Southwest (California) is estimated with Equation 1. There is a wide range of life cycle water withdrawal by generation source depending on whether or not cooling water is recirculated [4]. On the low end, the net water withdrawal displaced with a CdTe PV array in California exceeds 1700 L/MWh (Table 4). An alternative estimate for displacement is obtained with Ecoinvent (V. 2.2) unit process data on life cycle water withdrawal for California grid electricity generation sources. Based on this approach, the net water withdrawal displaced with a CdTe PV array in California exceeds 5600 L/MWh (Table 4).

Although life cycle water withdrawal by CdTe PV is low in comparison to most other electricity generation sources (Table 4), there are still opportunities to reduce water withdrawal during manufacturing. These efforts begin with understanding the manufacturing water balance. Figure 2 shows the balance of withdrawal, consumption, and discharge during CdTe PV module manufacturing in First Solar's Frankfurt-Oder, Germany plant in 2010.

During manufacturing, water is primarily withdrawn for production of ultrapure water (UPW) for use in module production, as well as for cooling tower water and site

TABLE IV

NET DISPLACEMENT OF WATER WITHDRAWAL (L/MWH) THROUGH DEPLOYMENT OF A CDTE PV ARRAY IN CALIFORNIA.

GS	f_{GS} (%) [9]	WW_{GS} [4] (L/MW)	Displacement (L/MWh)		Water Withdrawal by CdTe PV (L/MWh)	**Net Displacement (L/MWh)**	
			Based on Equation 1	Based on Ecoinvent (V. 2.2) unit processes for electricity by fuel [11]		Based on Equation 1	Based on Ecoinvent (V. 2.2) unit processes
Coal	7.59	2,500-98,400	190-7,465	3,240			
Oil	1.04	2,300-85,900	24-893	1,063			
Gas	52.47	2,300-85,900	1207-45,070	210			
Biomass	2.40	2,000-438,000	48-10,527	19			
Hydro	12.06	80	10-10	9			
Nuclear	16.25	3,900-120,000	634-19,500	1,450			
Wind	2.54	230	6-6	11			
Solar	0.25	800-1,900	2-5	11			
Other	5.40	80-438,000	4-23,664	29			
Total			2,124-107,138	6,042	382-425	**1,742-106,713**	**5,617-5,660**

irrigation. Water consumption is approximately one-quarter of withdrawal and is associated with cooling tower water evaporation and site irrigation, which account for 57% and 43% of consumption, respectively. Following on-site treatment, wastewater that has been treated for metal constituents (metal wastewater) is discharged to municipal sewer and non-metal wastewater is discharged to river. To reduce water withdrawal, non-metal treated wastewater could potentially be reused for site irrigation or as sanitary (gray) water.

Water balance data has been shown for First Solar's plant in Germany based on the availability of metering. Manufacturing process water use is consistent across First Solar plants, but there are climate-related differences in water use for irrigation and cooling tower operation. In addition, while on-site treated wastewater is discharged to river and sewer in Germany, it is discharged only to sewer in the United States, and only to river in Malaysia. However, the on-site wastewater treatment process is consistent across plants.

While data for on-site water consumption has been provided, estimates for indirect, upstream water consumption are not available. Estimates could potentially be obtained using the Ecoinvent database by subtracting water discharge from water withdrawal. However, because there are no categories for discharge to nature in Ecoinvent (V. 2.2) unit processes, a strict water balance cannot currently be achieved and is an area for further research.

IV. CONCLUSION

Life cycle water withdrawal by CdTe PV (382-425 L/MWh) is low in comparison to most other electricity generation sources. As a result, when deployed, CdTe PV arrays can displace water withdrawal from grid electricity by over 1,700-5,600 L/MWh in the U.S. Southwest. Primary contributors to life cycle water withdrawal are grid electricity, glass, and on-site water during manufacturing; steel, copper, inverters, and on-site water in the balance of systems; and electricity, chemical use, and transport during takeback and recycling. Developing a manufacturing water balance provides a baseline for reducing water withdrawal during manufacturing.

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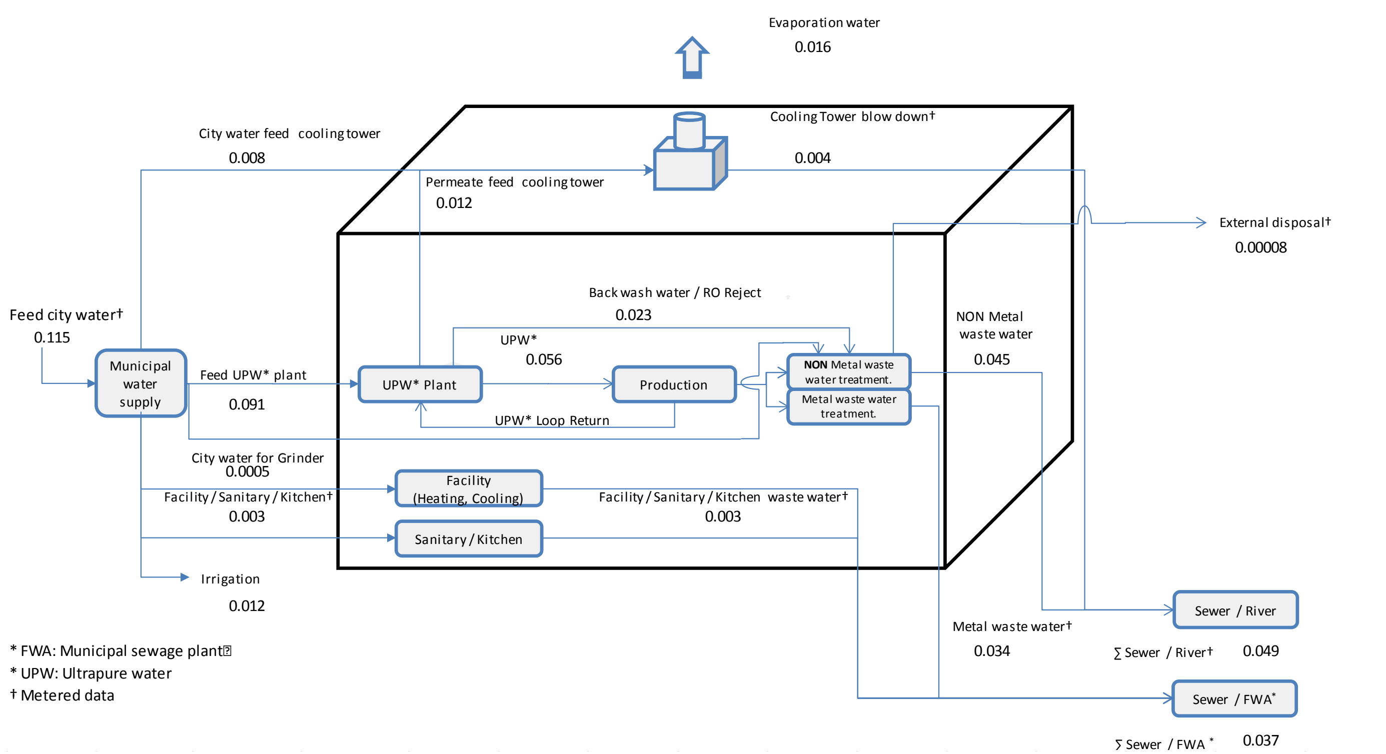

Fig. 2. Water balance (m^3 per m^2 module) for CdTe PV manufacturing in Frankurt-Oder, Germany in 2010. Specifically metered data are indicated by the symbol "†". Other data are estimated and therefore have a higher degree of uncertainty.

TITLE OF PAPER/ARTICLE/REPORT: Life Cycle Water Usage in CdTe Photovoltaics
COMPLETE LIST OF AUTHORS:Sinha, Parikhit; Meader, Amy; de Wild-Scholten, Mariska
IEEE PUBLICATION TITLE (Journal, Magazine, Conference, Book):Journal of Photovoltaics
LINK TO FINAL PUBLICATION: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6313879