Eco-Efficiency of CdTe Photovoltaics with Tracking Systems

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***Abstract* — Eco-efficiency is a management practice based on creating more value with less environmental impact. Tracking systems provide the benefit of boosting the specific yield (kWh/kWp/yr) of photovoltaic (PV) systems, therefore requiring fewer modules per kWh produced than fixed-tilt systems. Although life cycle balance of system (BOS) environmental impacts for tracking systems are higher per kWh produced than for fixed-tilt systems, this difference is counteracted by tracking systems requiring fewer modules manufactured upstream and decommissioned downstream per kWh produced than fixed-tilt systems. The life cycle carbon footprint and energy payback time/non-renewable energy payback time (EPBT/NREPBT) of utility-scale cadmium telluride (CdTe) PV systems in the U.S. Southwest range from 16-17 g CO2e/kWh and 0.6-0.7 yr, respectively, with impacts for tracking systems slightly (1-3%) lower than for fixed-tilt systems. Similarly, although tracking systems have slightly higher construction and operations and maintenance (O&M) costs per watt than fixed-tilt systems, these costs are counteracted by the improved specific yield of tracking systems, resulting in lower cost per kWh in the U.S. Southwest case study considered in this evaluation (global horizontal irradiation of 1952-2094 kWh/m^2/yr). Because tracking systems have the potential to create more value (kWh/$) with less life cycle environmental impact, they provide an eco-efficient strategy for improving the sustainability of PV systems. A key factor influencing the eco-efficiency of tracking systems is the tracking energy gain relative to fixed-tilt systems, which generally ranges from 10-24% over tropical and subtropical latitudes and is determined by project design, site latitude, and the proportion of diffuse horizontal insolation to global horizontal insolation at the site.**

***Index Terms* — BOS, LCA, horizontal tracking, cadmium telluride, eco-efficiency.**

I. Introduction

Eco-efficiency is a management practice based on creating more value with less impact [1]. In the case of PV, eco-efficiency translates to producing electricity at low cost and with low environmental impacts. Eco-efficient strategies are needed to improve the affordability of PV systems while maintaining their standing as a source of clean energy.

Tracking systems provide the benefit of boosting the plane of array irradiance (Fig. 1) and consequently the specific yield (kWh/kWp/yr) of PV systems; therefore requiring fewer modules per kWh produced than fixed-tilt systems. This benefit has consequences throughout the PV system life cycle, with fewer modules manufactured upstream and decommissioned downstream per kWh produced. However, tracking systems have greater mounting and cabling requirements than fixed axis systems and require some electricity during operation. The purpose of this evaluation is to consider the life cycle impacts of utility-scale CdTe PV with tracking systems to assess their eco-efficiency in relation to fixed-tilt systems. The mounting structures considered in this study are shown in Figure 2.

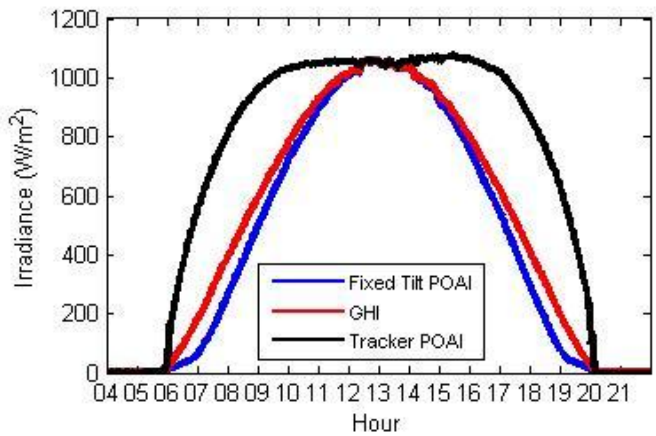

Fig. 1: Daily summer global horizontal irradiance (GHI) and plane of array irradiance (POAI) for fixed-tilt and single-axis horizontal tracking utility-scale CdTe PV systems in the U.S. Southwest. Note that fixed-tilt POAI is generally higher than GHI at this location, except in summer months.

Fig. 2: Mounting structures for (a) fixed-tilt and (b) single-axis horizontal tracking utility-scale CdTe PV systems.

II. Data Collection

A life cycle inventory (LCI) of fixed-tilt utility-scale CdTe PV has been developed based on a planned project in the U.S. Southwest (550 MWac Topaz Solar Farm in San Luis Obispo County, California) [2]. This evaluation considers the potential life cycle impacts of a utility-scale CdTe PV project

TABLE I

MATERIAL INVENTORY OF THE MOUNTING AND CABLING BOS COMPONENTS FOR A UTILITY SCALE CDTE PV PLANT.

Material	Unit	Mounting		Cabling	
		Fixed-axis	Tracking	Fixed-axis	Tracking
Steel (not Zn coated)	kg/m^2 module	0.0625	-	-	-
Steel (Zn coated)	m^2 Zn/m^2 module	0.6311	0.5609	-	-
	kg/m^2 module	10.14	15.79	-	
Aluminum	kg/m^2 module	0.1342	0.1405	0.0374	0.0471
Copper	kg/m^2 module	-	-	0.8798	1.166
Polyethylene Composite Material (HDPE)	kg/m^2 module	-	-	0.2866	0.4254
Tin	kg/m^2 module	-	-	-	0.0001604
Nylon	kg/m^2 module				0.008820
EPDM (synthetic rubber)	kg/m^2 module	0.0625	0.0709	-	-
Operating Electricity[a]	kWh/m^2 module	-	12.67	-	-

[a]Electricity for operating tracking actuators over a 30 year project lifetime.

in the U.S. Southwest if a single-axis horizontal tracking system had been utilized.

The life cycle inventory is structured in accordance with International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines for life cycle assessment (LCA) of PV [3], including BOS data for the following categories: mounting, cabling, inverter, transformer, site construction, and O&M. Mounting, cabling, and O&M data unique to tracking systems are utilized in this study, based on a detailed BOS inventory. Compared with fixed tilt systems, tracking systems have higher structural steel and cabling requirements and also use electricity during operation for tracking actuators (Table 1). Data for the other BOS LCI categories are common to both tracking and fixed-tilt systems and can be found in Section 2 of [2]. LCI data for CdTe PV module manufacturing in Malaysia and end-of-life collection and recycling in the U.S. are from [4] and [5], respectively.

II. METHODS

Life cycle assessment has been conducted with Simapro (V. 7.3.3) software and Ecoinvent (V. 2.2) unit processes. The LCA carbon footprint is estimated as CO_2 equivalent (IPCC 2007 GWP 100a Version 1.02 characterization method in Simapro) based on an integrated 100-year time horizon using the 2007 global warming potential factors published by the Intergovernmental Panel on Climate Change.

Energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself (Eq. 1).

$$EPBT = CED / (E_{agen} / \eta_G) \quad (1)$$

where CED is the cumulative energy demand of the system, E_{agen} is annual electricity generation, and η_G is grid efficiency (California grid; USEPA CAMX eGrid subregion [6]).

The Cumulative Energy Demand Version 1.08 characterization method in Simapro was used to estimate CED, which describes the primary (direct and indirect) consumption of fossil, nuclear, non-renewable biomass, and renewable energy sources along the life cycle of the system. Efficiency of the California grid (η_G) is approximately 32% which is similar to that of the average European grid.

The non-renewable energy payback time (NREPBT) is the EPBT calculated using the non-renewable (fossil, nuclear, non-renewable biomass) primary energy only for both the CED and η_G terms in Eq. 1. It therefore represents the time needed to compensate for the non-renewable energy required during the life cycle of the system.

LCA carbon footprint, EPBT, and NREPBT estimates are based on Q4 2012 average module conversion efficiency of 12.9% [7], a 30 year project lifetime [3], and a module degradation rate of 0.70%/yr [2]. For the fixed-tilt system, a specific yield of 1786 kWh/kWp/yr was used, whereas analysis of tracking systems considers a specific yield of 2162

TABLE II

SPECIFIC YIELD FOR FIXED-TILT AND TRACKING PV SYSTEMS IN THE U.S. SOUTHWEST.

	Site 1[a] (Altitude 333 m)		Site 2[a] (Altitude 1645 m)		Average		
	Fixed-tilt	Tracking	Fixed-tilt	Tracking	Fixed-tilt	Tracking	Tracking Energy Gain
Specific Yield (kWh/kWp/yr)	1813-1830	2186-2213	1740-1759	2112-2137	1786	2162	21%

[a]Site 1 and 2 global horizontal irradiation of 2094 and 1952 kWh/m^2/yr, respectively.

TABLE III
LIFE CYCLE CARBON FOOTPRINT, EPBT, AND NREPBT OF UTILITY-SCALE CDTE PV.

Mount	Mounting life	Module conversion efficiency	Specific Yield	Degradation rate	Carbon Footprint	EPBT	NREPBT
-	yr	%	kWh/kWp/yr	%/yr	g CO_2e/ kWh	yr	yr
Fixed-tilt	30	12.9	1786	0.70	16.77	0.635	0.662
Single-axis Tracking	30	12.9	2162	0.70	16.22	0.630	0.655
Difference					3%	1%	1%

kWh/kWp/yr [8], corresponding to a tracking energy gain (TEG; Eq. 2) of 21% (Table 2).

$$TEG = \left(\frac{SpecificYi\,eld_{\,Tracking}}{SpecificYi\,eld_{\,Fixed-tilt}} - 1 \right) \times 100\% \qquad (2)$$

II. RESULTS AND DISCUSSION

The LCA carbon footprint and EPBT/NREPBT of utility-scale CdTe PV systems in the U.S. Southwest range from 16-17 g CO2e/kWh and 0.6-0.7 yr, respectively (Table 3). Because the electricity grids considered in this evaluation are dominated by non-renewable power generation, EPBT and NREPBT differ only slightly.

Life cycle impacts for tracking systems are slightly (1-3%) lower than for fixed-tilt systems (Table 3). BOS impacts for tracking systems are higher than for fixed-tilt systems; however, this difference is counteracted in the module and end-of-life stages (Fig. 3). This is because tracking systems require fewer modules manufactured upstream and decommissioned downstream per kWh produced than fixed-tilt systems.

Within the BOS stage, life cycle impacts for tracking systems are primarily related to the use of galvanized steel in mounting structures (60%), with additional important impacts from cabling (7%), inverters (5%), transformers (4%), electricity to operate tracking actuators (11%), and raw material transport (6%) (Fig. 4). Construction accounts for a minor (2%) proportion of life cycle BOS impacts.

From an eco-efficiency perspective, tracking systems have slightly higher construction and O&M costs per watt than fixed-tilt systems due to the use of tracking equipment and associated cabling. However, these costs are counteracted by the improved specific yield of tracking systems, resulting in up to 10% lower cost per kWh in the U.S. Southwest case study considered here. Because tracking systems have the potential to create more value (kWh/$) with less life cycle environmental impact, they can be an eco-efficient strategy for improving the sustainability of PV systems (Fig. 5).

A key factor influencing the eco-efficiency of tracking systems is the energy gain that tracking systems provide over fixed-tilt systems. Based on PV energy simulations using First Solar's ISIS2 software, this advantage can be up to 22-24% for single-axis horizontal tracking considered in this study. Higher TEG can be achieved with tilted single-axis tracking and dual-axis tracking but with differing economics. Two variables that influence TEG are site latitude and the proportion of diffuse horizontal insolation to global horizontal insolation at the site (%DHI).

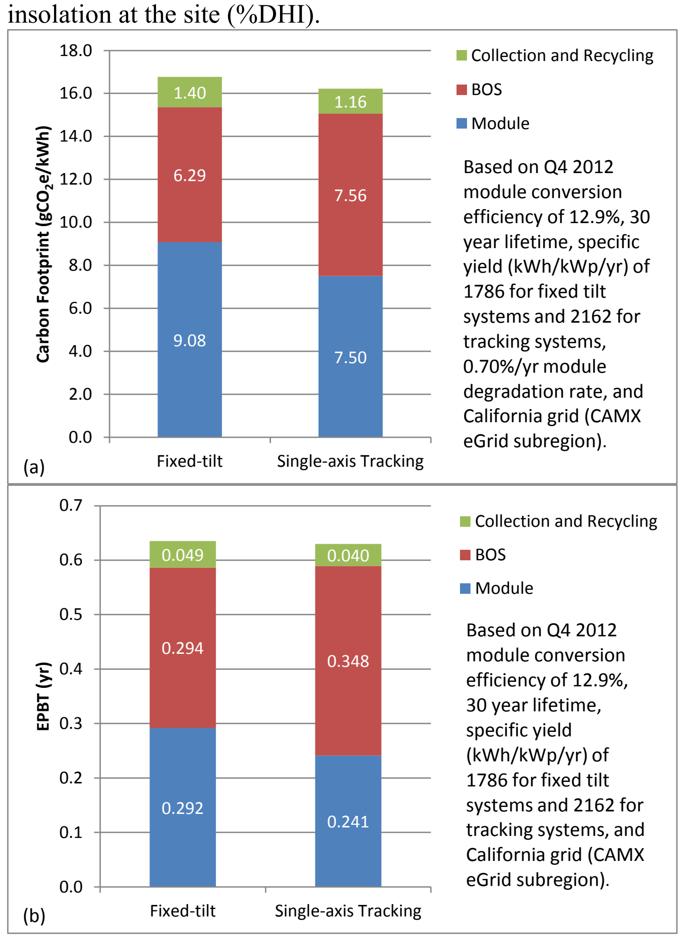

Fig. 3. a) Carbon footprint and (b) energy payback time of CdTe PV by life cycle stage for fixed-tilt and single-axis horizontal tracking utility-scale systems.

The advantage of tracking systems over fixed-tilt systems is their ability to harvest more direct beam irradiance, and since high diffuse lighting implies low direct beam, it is intuitive that sites with higher (>40%) diffuse light have relatively low TEG. The effect of site latitude on TEG is also straightforward; the lower the latitude, the closer the sun travels to the normal path of horizontal trackers, which equates to more plane-of-array insolation collected by the modules.

Given moderate (20-40%) diffuse light conditions, the gain in specific yield from tracking systems is expected to range from ~10-24% over tropical and subtropical latitudes (0-40˚). The specific cut-off for the economical use of tracking systems varies with respect to project design and economic value of the electricity generated, which is market-specific. Therefore, no single TEG value can be determined as the threshold for economical use of tracking systems; however, this value usually lies between 13-17%. Figure 6 shows global TEG variability generated from meteorological data provided by Meteonorm.

CONCLUSIONS

Depending on project design, site latitude, and diffuse light conditions, use of tracking systems can be an eco-efficient strategy for improving the sustainability of PV systems, potentially lowering both cost and life cycle environmental impacts per kWh generated.

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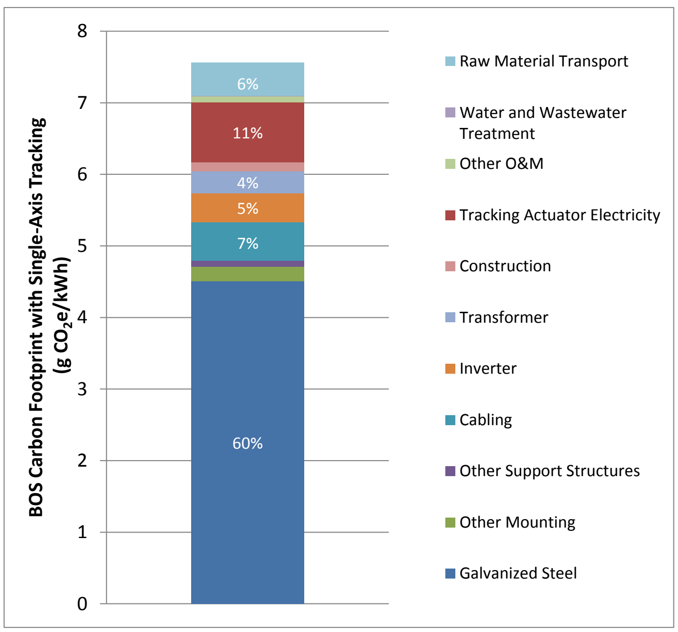

Fig. 4. BOS carbon footprint by component of CdTe PV single-axis horizontal tracking utility-scale systems. Based on Q4 2012 module conversion efficiency of 12.9%, 30 year lifetime, specific yield of 2162 kWh/kWp/yr, 0.70%/yr module degradation rate, and California grid (CAMX eGrid subregion).

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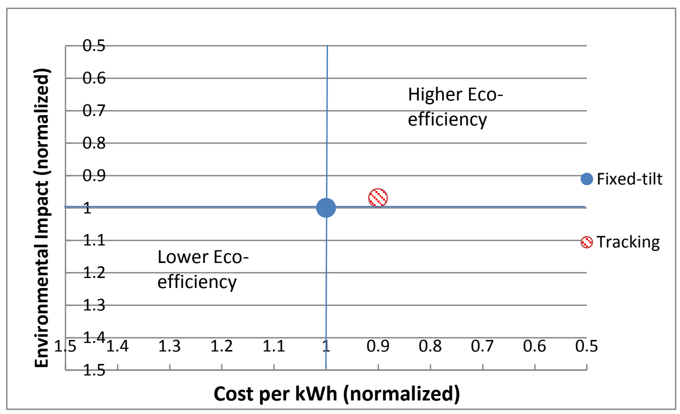

Fig. 5. Eco-efficiency of single-axis horizontal tracking relative to fixed-tilt CdTe PV utility-scale systems in the U.S. Southwest. Environmental impact based on carbon footprint and energy payback time in Table 3.

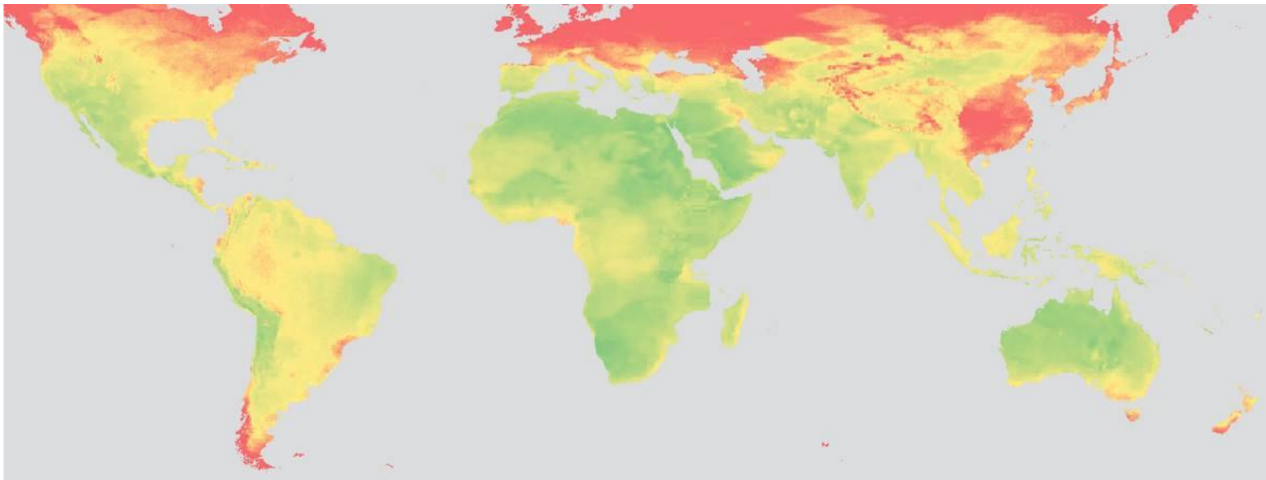

Fig. 6. Global Tracking Energy Gain (TEG) heat map. Green regions are likely to be favorable for deployment of tracking systems. Red regions are likely to be favorable for deployment of fixed-tilt systems. Yellow regions may be favorable or not for deployment of tracking systems, depending on system design and the economic value of electricity in those regions.

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