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Modeling Impacts of Tracking on Greenhouse Gas Emissions from Photovoltaic Power

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Abstract

A life cycle assessment (LCA) of photovoltaic (PV) power is conducted. The PV LCA is used to estimate the emissions impact of a common PV practice that has not been comprehensively analyzed by LCA: solar tracking. Relative to stationary mounting, solar tracking is found to decrease the greenhouse gas emissions of power from multi-crystalline silicon PV in most regions analyzed (by 0 to ~12%, or 0 to ~4 gCO_2e/kWh), and to increase the emissions of power from cadmium telluride PV in most regions analyzed (by 0 to ~12%, or 0 to ~4 gCO_2e/kWh). This dependence on cell type is explained by the interaction of tracker production emissions, module production emissions, and tracking energy gain. For both PV cell types, if the ratio of module production emissions to tracker production emissions increases in future, independent of absolute emission values, tracking will more commonly decrease PV carbon intensity. Conversely, if the ratio decreases, tracking will more commonly increase PV carbon intensity. Equations are presented to explain this relationship between module production emissions and tracker production emissions. These equations apply to emissions of all pollutants, not only greenhouse gases.

Keywords: photovoltaic (PV) power, life cycle assessment (LCA), greenhouse gas (GHG) emission, solar tracking

1. Introduction

Since 2008, solar tracking has grown from rare to common in photovoltaic (PV) power production. In the US from 2008 to 2014, 19 % of new utility-scale projects with cadmium telluride (CdTe) modules employed tracking (16 of 86 projects); in 2015 and 2016, the number was 56 % (44 of 79 projects), including locations outside the exceptionally sunny US southwest, such as Colorado and Tennessee (EIA 2016). For all PV module types, tracking was used on 53 % of cumulative and 70 % of new capacity at utility-scale sites in 2016 in the US (EIA 2016). The impact of solar tracking on emissions from PV generation has not been comprehensively analyzed by life cycle assessment (LCA). This study fills that gap. It provides a general methodology for estimating the emissions impact of adding performance enhancing equipment to PV, and applies this methodology to model the impact of solar tracking on emissions of greenhouse gases (GHGs). This paper refers to life cycle GHG emissions from AC electricity generation as "carbon intensity", and the units of grams-CO_2-equivalent/kilowatthour as "g_C/kWh".

Several LCAs analyzed the impact of solar tracking on carbon intensity, but with limited geographic scope and tracking set-ups that do not (and do not claim to) represent industry practice. Desideri et al. (2013) analyzed 1-axis tracking systems with 30º tilt in southern europe. In contrast, the industry norm for PV tracking is horizontal 1-axis tracking; in the US in 2016, 97 % of utility-scale tracking PV projects used horizontal 1-axis tracking (Bolinger et al. 2017). Two PV LCAs did analyze industry-representative tracking. Leccisi et al. (2016) found that horizontal 1-axis tracking reduced carbon intensity by 11 % and 1 % for mc-Si and CdTe PV, respectively, given installation in the US southwest. Sinha et al. (2013) estimated that tracking reduced the carbon intensity of CdTe PV by 3 % in the US southwest. This paper aims to build on these studies by calculating and explaining tracking's impact on PV carbon intensity over a range of locations.

2. Methodology

We developed a solar life cycle assessment tool (SoLCAT) following ISO 14040 standards for LCA (ISO 14040 2006) and IEA PV LCA guidelines. To estimate GHG emissions from PV power, SoLCAT integrates four elements: published PV life cycle inventories (LCIs), background emission factors from Ecoinvent, known physical correlations, and capacity factors from PVWatts, a software tool from the US National Renewable Energy Laboratory.

The goal of our LCA is to estimate the impact of solar tracking on the carbon intensity of PV power. The system is electricity production by PV. The functional unit is a kilowatthour of AC electricity supplied to the grid. In addition to electricity, the other system output analyzed is GHG emissions. These two system outputs combine into our central metric: GHGs emitted per AC electricity generated (g_C/kWh), or carbon intensity. PV electricity production can be elaborated as shown in Figure 1.

Figure 2 gives an overview of SoLCAT's operation and utilization of data sources. Our primary sources for PV LCIs are the IEA Report "Life Cycle Inventories & Life Cycle Assessments of PV Systems" (Frischknecht et al. 2015) and the ESU Report "Life Cycle Inventories of Photovoltaics" (Jungbluth et al. 2012). Sinha et al. (2013) provides an LCI of a horizontal 1-axis tracking system. For emission factors of background processes, our primary source is the Ecoinvent V3 database. In the absence of data, our model does not account for emissions from PV EOL processes.

SoLCAT converts amounts (a) to GHG emissions (e_{total}) using three general equations:

$$e_{total} = \sum_i e_{stage\ i} \tag{1}$$

$$e_{stage\ i} = \sum_j e_{input\ j\ to\ stage\ i} - \sum_k^{stages\ before\ i} e_{stage\ k} \tag{2}$$

$$e_{input\ j\ to\ stage\ i} = a_{input\ j\ to\ stage\ i}\ EF_j \tag{3}$$

where e is emissions (g_C), a is amount (e.g., kg-iron), and EF is emission factor (e.g., g_C/kg-iron). Amounts ($a_{input\ j\ to\ stage\ i}$) are provided by the PV LCIs or determined by parameters input to SoLCAT. Emission factors (EF_j) are provided by Ecoinvent or SoLCAT inputs. Miller et al. (2018) describes how SoLCAT input variables impact amounts and emission factors.

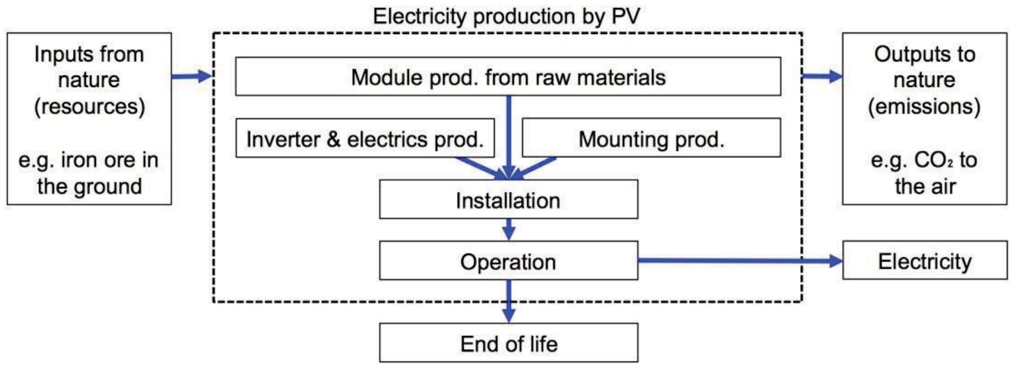

Figure 1. Life cycle stages of PV electricity production.

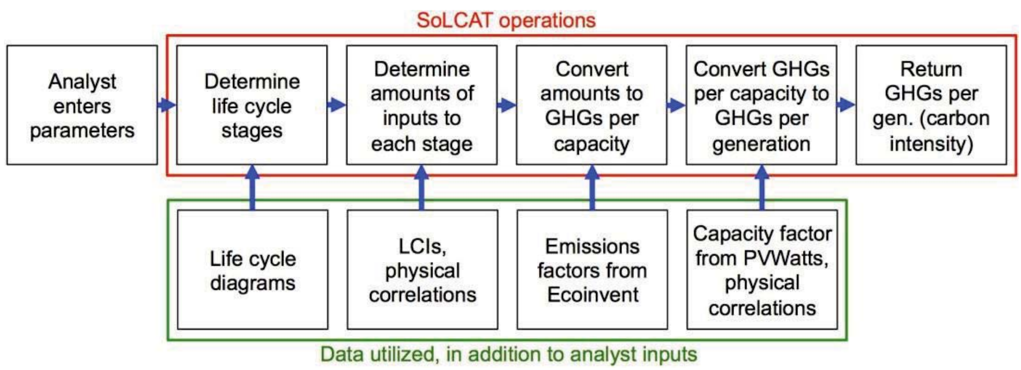

Figure 2. Flowchart of SoLCAT operations and utilization of data sources.

SoLCAT's last operation utilizes capacity factor estimates from PVWatts (Dobos 2014). As detailed in Miller et. al (2018), our model adjusts capacity factors from PVWatts to account for shading, snow, degradation, and tracker energy consumption, to calculate a lifetime average capacity factor (F). Carbon intensity is then calculated as:

$$I = e_{total} / (F c_g t_{hr}) \tag{4}$$

where I is carbon intensity (g_C/kWh), e_{total} is life cycle GHG emissions (g_C), c_g is rated power capacity, and t_{hr} is PV system lifetime (h).

Analysis of solar tracking's impact on carbon intensity requires calculation of tracking energy gain (TEG). TEG is the percent increase in PV power output that results from tracking the sun, relative to a fixed-position system, and can be estimated as

$$TEG = (\overline{P}_{AC,track} - \overline{P}_{AC,fixed}) / \overline{P}_{AC,fixed} \times 100\ \% \tag{5}$$

where $P_{AC,track}$ is the AC power output of a PV system with tracking, and $P_{AC,fixed}$ is the output of a PV system with fixed orientation and otherwise identical features (location, modules, etc.). The fixed base case orientation is assumed here to be irradiance-maximizing, with equator-facing azimuth and near-latitude tilt. The tracking system is horizontal 1-axis tracking with ± 45 º rotation limits.

3. Results and discussion

Using SoLCAT, base case results are calculated and shown in Figure 3:

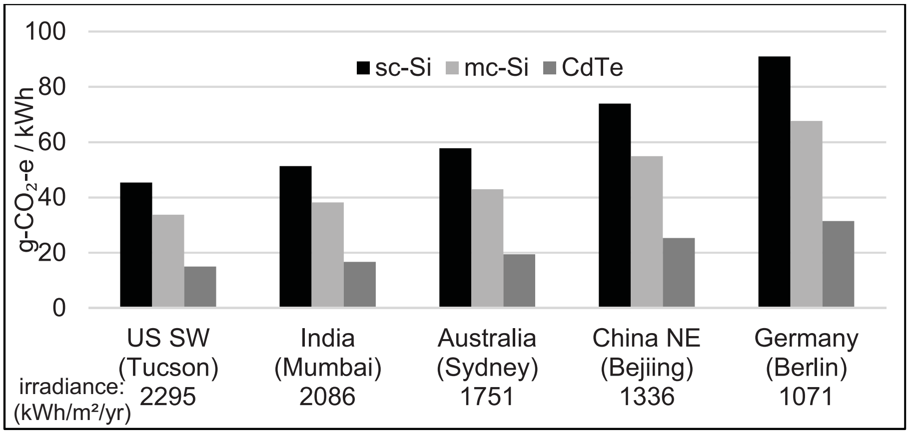

Figure 3. Carbon intensities of PV power installed in different locations circa 2015. Installation type is large-scale, open-ground, fixed-tilt. Lifetime is 30 years. Rated efficiencies are 17, 16, and 15.6 % for sc-Si, mc-Si, and CdTe. Degradation is 0.7 %/yr. GHG emissions of upstream electricity are 660 & 510 g_C/kWh for module and BOS production, assuming 2015 China & world averages.

We find that in the US southwest, for mc-Si PV, horizontal 1-axis tracking reduces carbon intensity by 12 % relative to the fixed-tilt base case (from 34 to 30 g_C/kWh), consistent with previous results (Leccisi, Raugei, and Fthenakis 2016). Tracking produces this reduction despite requiring ~50 % more structural metal and ~30 % more copper cable per module, compared to fixed mounting (Sinha et al. 2013). Emissions from producing tracker materials are offset by increased generation from tracking, such that overall emissions per generation decreases.

Analogous calculations are conducted for PV systems in 4 other locations and presented in Figure 4, which underlines several related findings. (1) location influences the emissions impact of tracking, via TEG; (2) tracking decreases the carbon intensity of mc-Si PV in most locations; (3) consistent with Sinha et al. (2013), tracking reduces the carbon intensity of CdTe PV in the US southwest by ~3 %; and (4) the US southwest is exceptional: for most locations analyzed, tracking increases the carbon intensity of CdTe PV power.

The dependence on location is driven by latitude and cloud cover. The greater the latitude, the greater the module incline that maximizes incident irradiance, and the more irradiance is lost by "reclining" to horizontal for 1-axis tracking. Greater latitude also means more atmosphere for sunlight to travel through. This increases light scattering, as does greater cloud cover. The greater the fraction of ambient light that is scattered (i.e., diffuse), the less energy there is to be gained from tracking the sun's non-diffuse direct beam irradiance. Lower tracking energy gain (TEG) means less extra electricity over which to amortize extra emissions from tracker-production. For both module types, this explains why, as TEG decreases left to right in Figure 4, tracking's emissions impact increases.

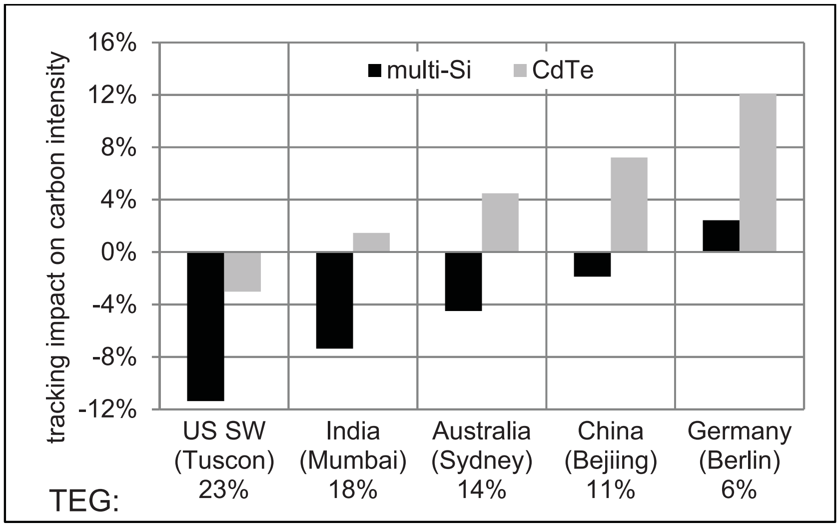

Figure 4. Relative impact of horizontal 1-axis tracking on PV carbon intensity in different locations, for mc-Si PV and CdTe PV.

The varying impact by module type can be explained with the following equations. Let:
$T \equiv$ factor by which tracking increases electricity generation.
$e_{f,i} \equiv$ emissions of fixed PV system (g_C). i = mc-Si or CdTe
$e_t \equiv$ emissions from adding tracking (g_C)
$E_f \equiv$ generation from fixed PV system (kWh)
$E_t \equiv$ generation from tracking PV system (kWh)
$I_f \equiv$ emissions per generation (carbon intensity) of fixed PV system (g_C/kWh)
$I_t \equiv$ emissions per generation (carbon intensity) of tracking PV system (g_C/kWh)
$M \equiv$ factor by which tracking changes carbon intensity

$$\begin{aligned} M &= I_t / I_f \\ &= [(e_{f,i} + e_t)/E_t]/[e_{f,i}/E_f] = [(e_{f,i}+e_t)/(TE_f)]/[e_{f,i}/E_f] \\ M &= (e_{f,i}+e_t)/(Te_{f,i}) \end{aligned} \tag{6}$$

Consider Eq. (6) when $e_{f,i} \gg e_t$, i.e., when emissions from module production are much larger than emissions from tracker production:

$$M_{f\ large} = 1/T \tag{7}$$

$M_{f\ large}$ will always be less than 1, because T always exceeds 1. In other words, for a module type with large production emissions, adding tracking always reduces carbon intensity. This explains why adding tracking reduces the carbon intensity of mc-Si PV in most locations (blue bars in Figure 4). Multi-Si module production is significantly more carbon intensive than CdTe module production, as seen in Figure 3 and previously reported (Frischknecht et al. 2015). $e_{f,multi\text{-}Si}$ is approximately 11 x e_t whereas $e_{f,CdTe}$ is approximately 5 x e_t . Eq. (6) thus also explains why adding tracking increases CdTe PV's carbon intensity in most locations (red bars in Figure 4):

$$M_{CdTe} \approx (e_{f,CdTe} + e_{f,CdTe}/5)/(Te_{f,CdTe}) = 1.2/T \tag{8}$$

For M_{CdTe} to be less than 1, T must exceed 1.2. In other words, CdTe PV requires TEG above 20 % for tracking to reduce its carbon intensity, a TEG only possible in exceptionally sunny regions like the US southwest.

4. Conclusion

A modeling tool (SoLCAT) is presented. SoLCAT estimates GHG emissions from solar PV generation under a broad range of conditions, partly by combining life cycle inventories and PV performance models. Using this tool, we find that solar tracking decreases the GHG emissions of power from multi-crystalline silicon PV in most regions analyzed (by 0 to ~12 %, or 0 to ~4 gCO_2e/kWh), and increases the emissions of power from cadmium telluride PV in most regions analyzed (by 0 to ~12 %, or 0 to ~4 gCO_2e/kWh). For any PV cell type and any emitted pollutant, if the ratio of module production emissions to tracker production emissions increases in future, independent of absolute emission values, tracking will more commonly decrease PV emissions intensity.

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