TRACKER ACCURACY: FIELD EXPERIENCE, ANALYSIS, AND CORRELATION WITH METEOROLOGICAL CONDITIONS

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ABSTRACT

Tracker performance is a significant factor in the energy production of PV systems, especially concentrating photovoltaic (CPV) systems. The nonlinear relationship between CPV optic pointing accuracy and energy production means that simple metrics such as mean pointing accuracy are not sufficient for predicting performance of these systems.

Additionally, trackers are currently a significant component of system cost. Understanding the real causes of tracking errors in the field (as well as which types of errors have a less significant impact on energy production) is an important step towards the development of lower-cost tracking systems.

In this paper we present a collection of real-world data, including tracking error and corresponding meteorological data, gathered over a period of months from commercial solar trackers installed at Instituto de Sistemas Fotovoltaicos de Concentración S.A. (ISFOC) in Puertollano, Spain. We present several relevant mathematical tools for analyzing this data, and draw conclusions about the implications of tracking errors for system energy production.

OVERVIEW

Accurate and verifiable sun tracking is a key challenge facing the solar and solar tracker industries, especially in the fields of concentrating photovoltaics (CPV) and concentrating solar power (CSP). The variations in sun elevation, wind loading, and other weather conditions over the course of a year and across different sites makes it difficult to predict the behavior of a tracking system without real-world test data. Even in the development stages of a tracker, control algorithm, system, or site installation, it is difficult to produce quantitative data demonstrating tracking performance.

Array output (power, current, and so on) is not sufficient information to determine tracking accuracy, as there are many conditions that can contribute to changes in overall system performance (including irradiance, ratio of direct to global irradiance, cell temperature, wind speed as it affects convective cooling, and deflection across the array itself due to weight or wind loading).

In addition, the lack of existing standards for reporting tracker performance makes it difficult to evaluate and compare tracker manufacturer specifications, and understand how they will translate to real-world operating conditions.

Finally, different solar technologies (HCPV, LCPV, CSP, and dual- and single-axis tracked flat-plate crystalline silicon) each have particular relationships between generated power and tracking error in each axis, leading to different tracking requirements for each technology.

These challenges call for a method for accurately characterizing both absolute and relative tracking accuracy, in the field, under a variety of weather conditions.

In this paper, we present data on tracker error gathered over a period of months from commercial solar trackers installed at (ISFOC). We also draw conclusions about factors that produce tracking error and detail our methods of measurement and analysis.

TYPICAL TRACKING ERROR

Tracker pointing error can be measured at any instant with two parameters: error in azimuth and error in elevation. CPV and CSP systems have to point at the sun with great accuracy, with the requirement increasing roughly in proportion to the concentration factor. The pointing error that the system can tolerate without substantial loss in power output is called the acceptance angle; different firms use different metrics for what constitutes “substantial” loss of power.

Modern high-concentration photovoltaic (HCPV) concentrators advertise acceptance angles of ±1-2°. (For example, [1].) Some firms in the industry claim tracking accuracy better than ±0.1° without data on tracking error to substantiate their claims. This ±0.1° may be the accuracy of an algorithmic calculation, not the real pointing accuracy of the tracker.

The salient question is whether typical tracking error for competitively priced commercial trackers is small compared to acceptance angle, or of the same magnitude.

METHODS

Instrumentation

The tracking error data were logged by a GreenMountain Engineering Trac-Stat SL1, a diagnostic instrument for measuring tracker error [2].

The meteorological data came from the weather station at ISFOC's facility. The direct normal irradiation (DNI) was measured by a Middleton DN5 pyrheliometer. Temperature was sensed with a R. M. Young model 41003 thermometer with a multiplate radiation shield. Wind velocity was measured with an R. M. Young model 03002 wind vane and anemometer.

Data were gathered continuously for 8 weeks by ISFOC staff in March, April, and May of 2009. The approximate location of the facility is latitude 38.75° N, longitude 4.09° W.

Data processing

The SL1 measured tracker error every 15 seconds, when it was able to locate the sun; otherwise null data was recorded and the occurrence flagged. The meteorological data were recorded once per minute. The data were merged using a Python script that converted all of the measurements to a common time base. The meteorological data were assigned to the SL1 measurement nearest in time, and the extra SL1 data were discarded.

Ephemeris calculations were performed to determine the sun position, and thus the target azimuth and elevation of the tracker, as a function of time, using Pysolar, a free Python library written by the author [3].

The total dataset consists of roughly 180,000 datapoints. Final calculations and charting were performed with Python and Matplotlib [4].

A representative sample of the time series data logged is shown near the end of this paper in Figure 6.

ANALYSIS

Energy lost due to acceptance angle

Successful tracker control algorithms typically use a control strategy that is a hybrid between open-loop control, i.e. naïve prediction of sun position through ephemeris calculations, and closed-loop control, i.e. error correction based on the sensed position of the sun. The open-loop component is required because the sun can be obscured by clouds, eliminating or distorting the feedback signal.

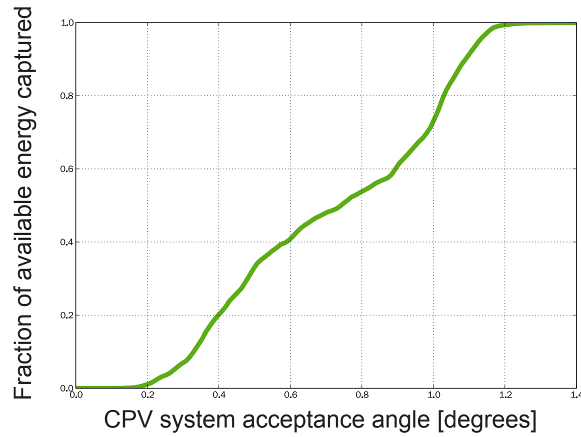

Fig. 1. Energy captured as a function of acceptance angle

The closed-loop component is required because of the expense of eliminating pointing errors-- due to assembly, ground leveling, encoder mounting, inexact calibration, weight-induced deflection, and so forth. All of these errors can be made arbitrarily small at some cost, but CPV is nothing if not a play on cost relative to conventional PV. The challenge, then, is to build a cost-competitive tracker that points accurately enough to keep the sun within the tracked modules' acceptance angle.

Also, generated module power cannot easily serve as an instantaneous, solitary feedback signal, as the power also depends on the impedance of the system's maximum power point tracker (MPPT), which is continuously varied for the most efficient power extraction. Coordinating realtime accommodation between tracker and MPPT is a nontrivial task, even if the two components were designed contemporaneously by the same engineering team, which is not usually the case.

Recent research [5] performed by GreenMountain and ISFOC has suggested that typical tracker errors are not negligible relative to typical acceptance angles. This contradicts the conventional wisdom that tracker errors occur mostly when little radiation is available for capture, e.g. cloudy days, dawn, and dusk. In fact, our measurements show that modules mounted on the CPV tracker studied for the 8 weeks logged would start to shed energy due to tracker error at acceptance angles below ±1.2°. 25% of available energy is lost at ±1.0°, and 60% of energy is lost at ±0.6°.

The energy rejection curve is shown in Figure 1. The calculations assume that the acceptance angle is a sharp cut-off, which is an assumption realistic enough for this study.

Additionally, the time-varying component of the SL1 error measurement is a lower bounding estimate of error, in that beyond the constant angular offset between the SL1 and the immediately local module structure, there will be misalignment module-to-module, misalignment within modules, and some deflection of the whole array. These errors all reduce the effective system acceptance angle.

Wind loading

Average wind velocity can be misleading. Figure 2 shows wind velocity as a function of direction over the course of 2 months at ISFOC's facility in Puertollano, Spain. The adjacent plot, Figure 3, shows the drag force on a flat plate from the wind as a function of direction for the same period in the same location, normalized to the drag corresponding to the highest wind speed measured. The difference in relative magnitude occurs because the drag force scales with the square of the wind velocity.

In considering the effect of wind on trackers, it is necessary to take into account the changing orientation of the tracker. Figure 5 is a hex-bin plot that shows the total tracking error plotted against force from wind loading. The wind loading force is assumed to be proportional to the projected area of the tracker in the direction of the wind (the dot product of the tracker's normal vector and the wind's heading) and the square of the wind velocity. Brighter regions in the plot show higher densities of tracker error. The dashed line shows the median tracking error, 0.76°.

Relative to the median tracking error, we can see that high wind forces do affect the tracker's accuracy. When the wind force is high on either side of the tracker (because the wind is strong and the tracker is oriented across the wind), the error deviates from the median with sense that matches the wind force-- these are the white "flags" protruding at the upper right and lower left sides of the central vertical stripe.

CONCLUSIONS

Techniques and tools now exist that allow tracker error to be measured in the field and compared to meteorological data using only commercial, off-the-shelf equipment and statistical analysis. Extended observation of a production tracker in actual operation, along with previous monitoring of similar trackers [5], has shown that tracker error is of the same magnitude as acceptance angles claimed by CPV manufacturers. Error due to wind loading is a measurable quantity that can approach acceptance angles of current modules; site assessors would do well to consider expected wind regime in their assessments.

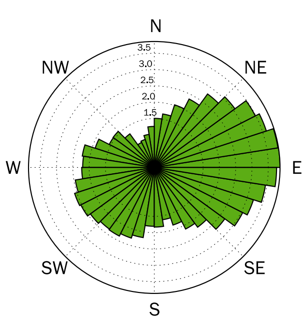

Fig. 2 Average wind velocity [m/s] vs. direction

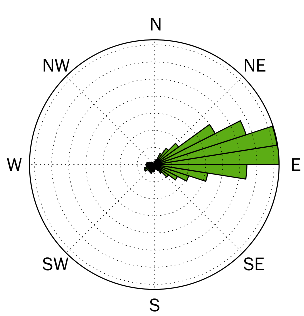

Fig. 3. Drag force [% of max] vs. direction

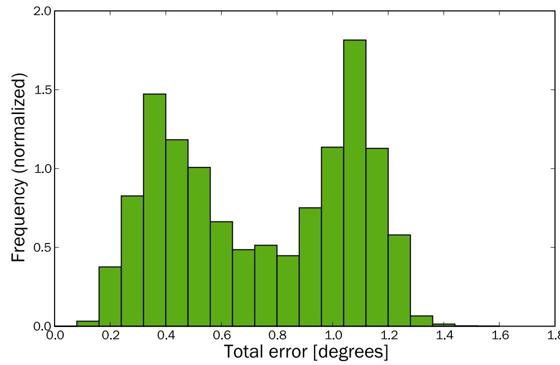

Fig. 4. Histogram of total tracking error

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[2] M. Davis, J. Lawler, J. Coyle, A. Reich, T. Williams, "Machine Vision as a Method for Characterizing Solar Tracker Performance", *33rd IEEE PVSC*, 2008.

[3] http://pysolar.org "Pysolar is a collection of Python libraries for simulating the irradiation of any point on earth by the sun. It includes code for extremely precise ephemeris calculations."

[4] http://matplotlib.sourceforge.net/ "Matplotlib is a python 2D plotting library which produces publication quality figures in a variety of hardcopy formats and interactive environments across platforms."

[5] M. Davis, T. Williams, M. Martínez, D. Sanchez, "Understanding Tracker Accuracy and Its Effects on CPV", ICSC-5, 2008.

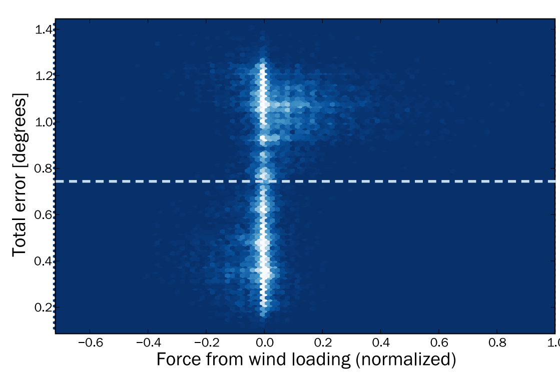

Fig. 5. Tracking error vs. wind loading

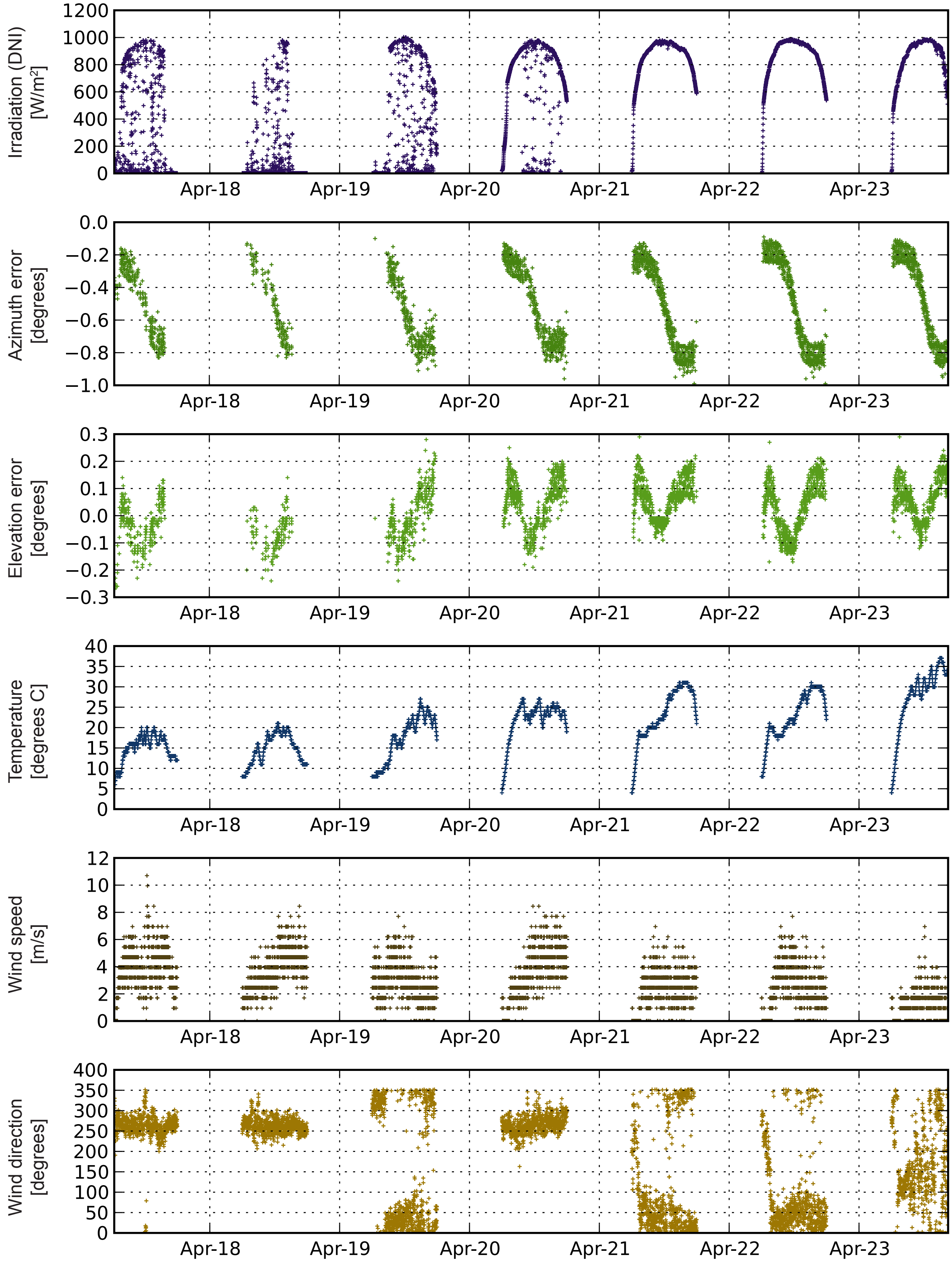

Fig. 6.. Representative time series data collected at ISFOC in spring 2009