Strategies to Optimize and Validate Backtracking Performance of Single-Axis Trackers on Sloped Sites

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***Abstract*—Tracking optimization is one strategy that PV plants can employ to maximize energy production on sites with variable terrain. Three different backtracking modes (baseline, commissioned, and SmarTrack™) are considered here for analysis and result in demonstrated different energy production profiles. An alternating operation validation strategy is described to compare these different modes of operation in the field, and experimental results for one example site are presented. A methodology to simulate this behavior is described, showing results both for the validation period as well as annual results.**

Keywords— single-axis tracking, backtracking, photovoltaic, shading, slope

I. Introduction

As PPA rates have reduced drastically over time, any innovations which enable increased energy harvest for a PV plant are vital to ensure long term viability of the project. Singe-axis tracking structures are one such strategy that have long been used to increase the energy capture per area of a site, changing the module orientation throughout the day to follow the sun's position. These systems commonly backtrack, moving to a flatter position in the morning and the evening to avoid module shading that can cause a non-linear power loss. Traditional backtracking was developed to avoid module shading assuming an ideal horizontal site. However, real-world sites often cannot meet this ideal even if expensive grading is performed; in addition to uneven terrain, post height installation tolerances lead to additional row height differences. Of particular concern here are cross axis slopes (i.e. E-W slopes for tracking systems with a N-S axis), where morning and evening hours will experience either shading or overconservative positioning depending on the direction of the slope. Note that industry standard modeling software cannot model this behavior without complex post-processing, so the effects of slope and row height variation are too often ignored. Previous studies have compared backtracking geometries like these to flat geometries and their relative theoretical effects on energy production [2-3].

II. Backtracking Strategies

Three different backtracking strategies are considered in the following work:

A. Baseline Backtracking

Baseline backtracking uses the generic backtracking model with the layout row spacing and does not take the effect of slope into account. This will cause shading during the time of day when the modules are facing upslope, and conversely cause over-conservative tracking during the time of day when the modules are facing downslope.

B. Commissioned Backtracking

All Array Technologies sites are carefully commissioned to avoid shading by adjusting the AM and PM row spacings manually within the generic backtracking model. In practice, this means that the row spacing is decreased during times when the modules are facing upslope to avoid shading. This practice can be quite effective in regaining potential lost energy due to shading, but does not represent the ideal solution.

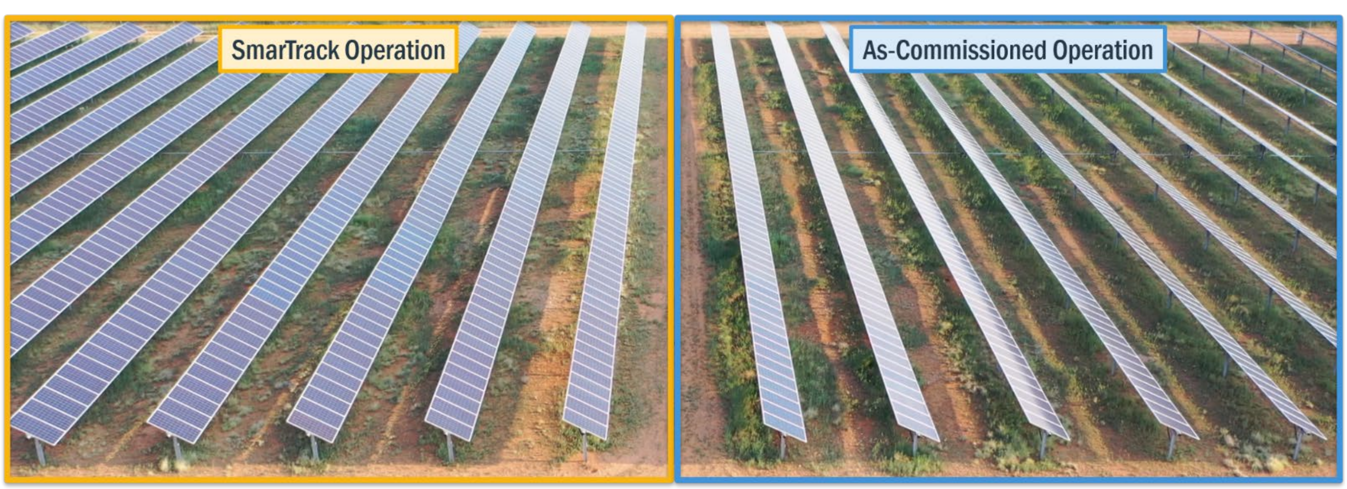

Fig. 1. Alternating operation example for SmarTrack™ and Commissioned Backtracking on odd and even days.

C. *SmarTrack™*

SmarTrack™ is Array's innovative controls platform that includes backtracking optimization for sloped terrain. SmarTrack™ uses a tracking algorithm that takes slope and row to row height variation into account, and implementation includes a learning period where these necessary parameters are determined automatically to maximize output production. Compared to commissioned backtracking, SmarTrack™ tracking angles are truly optimized for the site terrain and often have a different shape to the tracking curve.

A visual example of side by side commissioned and SmarTrack™ motorblocks are shown in Fig. 1. Both cases are shown to avoid shading on the modules, but the light band on the ground apparent in the as-commissioned operation indicates there is sunlight that is not captured.

III. In-Field Gain Evaluation – Alternating strategy

Following the SmarTrack™ learning period, an evaluation period commences to determine the improvement in production. During the testing, the inverters are divided into two groups (A and B). Group A operates in SmarTrack™ mode on even days of year while group B operates with previously commissioned settings; on odd days, the groups switch operation. To determine the gain, all SmarTrack™ production during the evaluation period is summed and compared to the sum of all commissioned production. This validation strategy allows minor location, weather, soiling, or performance biases to cancel over time.

An example is shown in Fig 2., where the site was divided into a checkerboard pattern with four symmetrical and adjacent inverter quadrants. Each quadrant consists of four tracker blocks, each powered by a separate motor and controller. On alternating days, half of the 16 tracker blocks operated in SmarTrack™ mode and half in the commissioned backtracking mode.

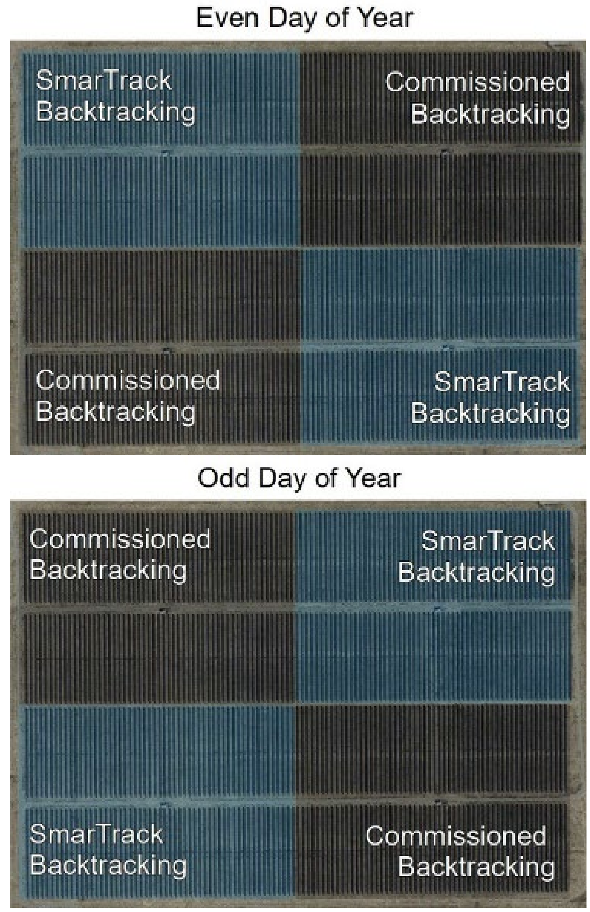

Fig 2. Alternating operation example for SmarTrack™ and commissioned backtracking on odd and even days.

Fig 3. In-field site for gain evaluation, looking downslope to the east.

IV. In-Field Results

A. *Site Information*

The site considered here is a 12.5 MWdc PV plant located near Albuquerque, NM. The site exhibits a mean absolute slope of around 2% and is relatively monosloping to the east. Current and voltage inverter data is collected from the site at a frequency of 30 seconds for analysis.

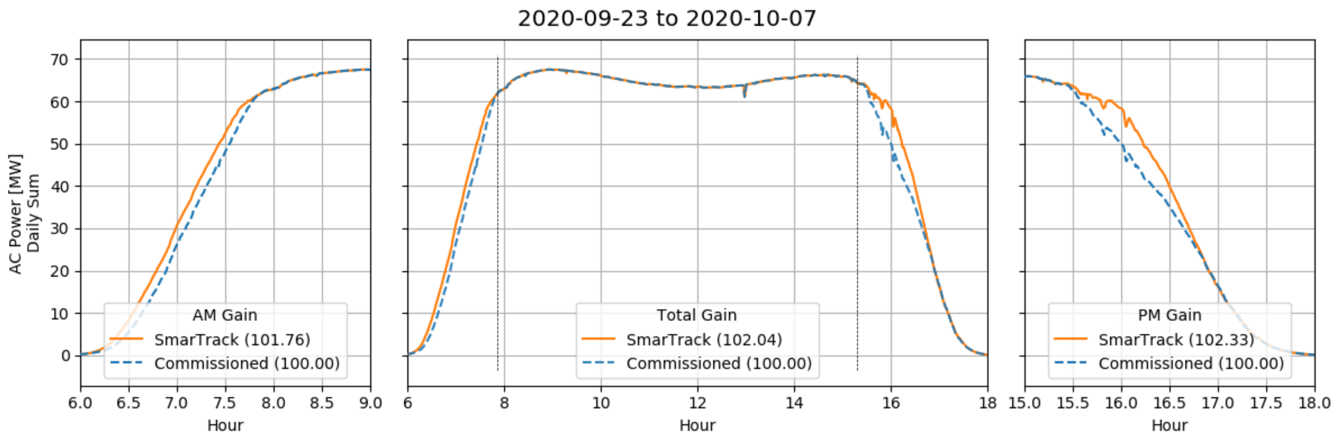

Fig 4. Summed SmarTrack™ and commissioned production for all inverters during alternating evaluation period.

B. Measured Period SmarTrack™-Commissioned Gain

Following a learning period of roughly two weeks, alternating SmarTrack – commissioned operation (as described above) was executed for 16 mostly clear days from 9/23/2020 through 10/27/2020. Data was unavailable for one day (10/2) due to a communication outage. The 30 second data was filtered and interpolated for midday values <1 kW to exclude a few brief inverter dropouts. Midday performance between backtracking periods was averaged to disregard any inverter anomalies during those times. The results are shown in Fig. 4, indicating an overall SmarTrack™ gain over previously commissioned settings during the validation period of 2.04%. SmarTrack™ optimization is able to recover energy by tracking less conservatively in the morning (when the modules are tilted toward the downslope); in the afternoon, SmarTrack™ is able to delay the onset of backtracking and still avoid late day shading due to the adjusted shape of the tracking curve.

The annual gain for this site is expected to be slightly lower than the evaluation period gain since the evaluation period had primarily clear conditions. The details of the annual gain estimation are explained later in this paper.

C. SmarTrack™-Baseline and Commisioned-Baseline Experiments

Additional experiments were conducted on this site to examine the performance effects of operating in the three modes described in Section II. This included a 4 day period of SmarTrack™-baseline alternating operation (10/8/2020-10/11/2020) and a 2 day period of commissioned-baseline alternating operation (10/12/2020-10/13/2020). The same simple filtering described in the previous section was applied. The results of these experiments along with the SmarTrack™ commissioned results are summarized in Table 1. Select days' afternoon profiles of the three cases for one inverter are overlaid in Fig. 5.

The differences in the tracking modes are illustrated distinctly:

- The baseline case waits the longest to begin backtracking, but the shading that results from this is apparent in the steep drop on the power curve.
- The commissioned case tweaks the row spacing to avoid shading; however, backtracking begins quite early and leaves energy on the table. There is also likely some shading occurring late in the afternoon after the commissioned tracker angle curve intersects the SmarTrack™ curve.
- The SmarTrack™ curve starts backtracking much closer to the baseline case than the commissioned case, seemingly "shifting" the baseline tracking curve to the left. This results in the highest production of the three cases.

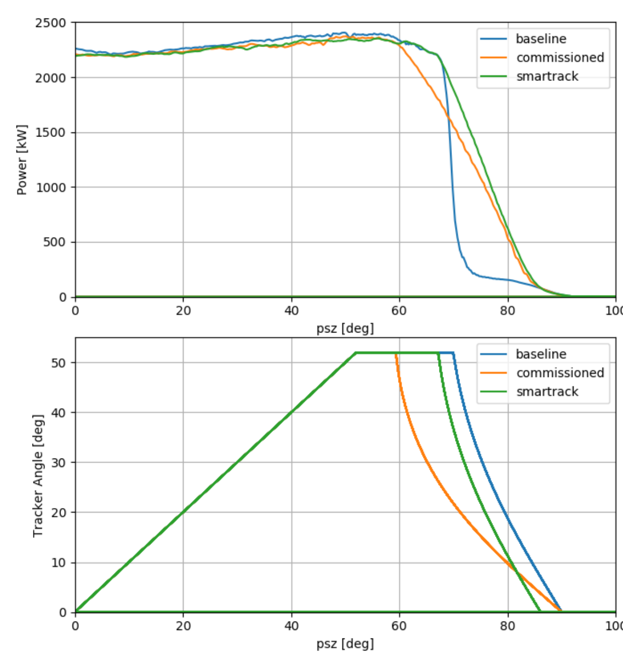

Fig 5. Select days' afternoon backtracking mode production curves (top) and tracking curves (bottom) overlaid for inverter 4.

TABLE I. SUMMARY VALIDATION PERIOD RESULTS

Validation Case	Validation Period	Observed Gains (all invs/rep invs)	Predicted Gains
$\frac{SmarTrack}{Commissioned}$	9/23-10/7, excl. 10/2 (14 days)	2.04%/1.96%	2.42%
$\frac{SmarTrack}{Baseline}$	10/8-10/11 (4 days)	4.42%/4.26%	5.77%
$\frac{Commissioned}{Baseline}$	10/12-10/13 (2 days)	2.53%/2.43%	3.21%

V. PREDICTION METHODOLOGY

The site production for the baseline, commissioned, and SmarTrack™ cases are modeled using PlantPredict [3]. This software is ideal for this analysis, as it allows subhourly resolution and the input of time series tracking angles. The SDK also allows the following process to be easily automated, greatly improving the time to simulate [4].

For this analysis, the power plant is created with the as-built components and site design. Only two inverters are modeled to avoid long simulation times on larger sites, chosen based on how close their learned slopes are to the site average. For this site, the validation period gain for representative inverters 3 and 4 is 1.96% compared with 2.04% using all inverters. All further comparisons reference the representative inverter results only. Each inverter is modeled as having only one DC field, using the average of parameters from all motor blocks that compose that inverter. Lacking detailed information about the site conditions (soiling, degradation, etc.) the dc capacity of the representative inverters is scaled to match the measured and predicted midday production between 11 a.m. and 1 p.m. during the analysis period (0.96).

Unfortunately, the GHI sensor on site shows a persistent skew consistent with off-azimuth orientation. This can have a large impact on predictions that rely heavily on the shoulder hour accuracy, so clear sky GHI is used as a substitute along with measured ambient temperature at 1 minute resolution. This should be a relatively good estimate since the weather during the validation period was particularly clear.

Time series tracking angles at the same resolution are determined externally using Array's algorithms and the site parameters, including the actual row spacing, module height, and the learned AM and PM slope/row to row height variation. These angles are imported into PlantPredict and used in lieu of the internally calculated tracking angles to represent the tracking behavior appropriately for each case.

In all, 6 simulations are run: baseline, commissioned, and SmarTrack™ using both the AM learned slope and the PM learned slope. These simulation results are then spliced together at noon to create 3 aggregated simulations, one for each operation case. This methodology was used to simulate the gain during the three validation periods using the clear sky GHI and measured ambient temperature. The methodology was then repeated using a TMY weather file to predict the annual gain.

VI. PREDICTED RESULTS AND DISCUSSION

A. Validation Period Results

The results for the validation periods are shown alongside the measured gains in Table 1. Despite the simplifications in the modeling, including using clear sky GHI, scaling the DC to match site production, and modeling each inverter using average motor block parameters , the SmarTrack™ gain over commissioned shows agreement within 0.5 percentage points.

The commissioned gain over baseline is overestimated by about 0.8 percentage points. The oversimplifications mentioned above may contribute to this, but a more significant factor appears to be a discrepancy in the shading behavior. As observed in Fig 6., the measured profile shows a more gradual decrease compared to the sharp drop in the predicted production. The modeling methodology likely plays a role, estimating that the string production drops to 0 with any shading over 1% (this is known to overestimate the electrical shading effect). The combiner data shown in Fig. 7 indicates that there are many combiners that do experience this sharp drop. However, this is counteracted by combiners that show a slower, zig-zagging decline indicative of parts of the array coming in and out of shade.

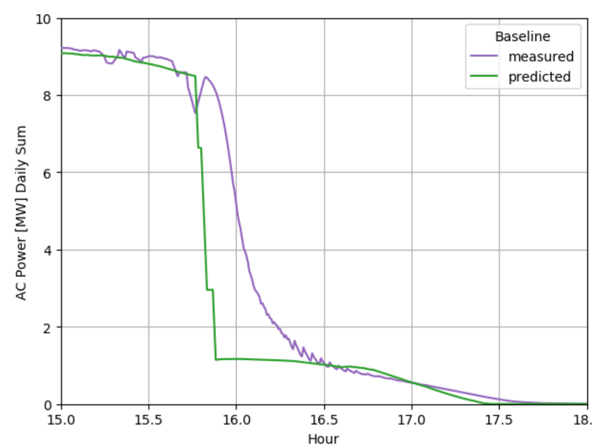

Fig 6. Summed measured and predicted baseline production 10/12-10/13 alternating evaluation period.

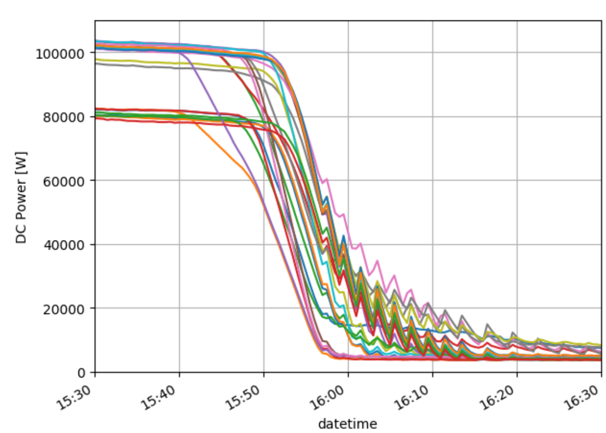

Fig 7. All combiners for inverter 4 on 1/13 operating in baseline backtracking mode.

This behavior is likely due to row to row height variation in addition to varying slopes within a motor block, which makes it a challenge to model the electrical losses accurately. The PV strings in a motor block will experience different levels of shading losses, at least until the sun is low enough that all the rows are in shade to at least one cell row. A simplistic approach of representing a motor block as being monoslope with no row-height variation leads to overestimation of the electrical losses.

We have developed a methodology to perform a weighted averaging of simulations with electrical shading on and with electrical shading off, to better fit the measured power profile when shading is significant. The new method allows more accurate estimation of the site-specific losses, which in turn provides more accurate estimation of the annual loss recovery. The method will be presented in future communication.

The overestimates in the SmarTrack™ vs. commissioned and commissioned vs. baseline gains aggregate into a larger 1.5 percentage point overestimate in the SmarTrack™ vs. baseline gain.

B. *TMY Results*

The same methodology described in Section 5 was repeated with a TMY weather file to predict the annual gains. The results are shown in Table 2. The differences between the predicted and measured gains during the validation period are taken into account to give a corrected value that is likely a better estimate.

TABLE II. SUMMARY TMY RESULTS (REPRESENTATIVE INVS)

Validation Case	Annual Gains	Annual Gains, Corrected
$\frac{SmarTrack}{Commissioned}$	+1.93%	+1.47%
$\frac{SmarTrack}{Baseline}$	+4.21%	+2.70%
$\frac{Commissioned}{Baseline}$	+2.25%	+1.47%

VII. CONCLUSION

Analysis of SmarTrack™ backtracking on a gradually sloping site was shown to bring significant gains over as-commissioned settings (2.04%). Additional experiments were performed to show the effects of operating in three different modes: baseline (generic backtracking, as-built parameters), commissioned (generic backtracking, adjusted row spacing), and SmarTrack™ (backtracking accounting for cross-axis slope and row height variations, after automatic optimization per Array's proprietary algorithm). This demonstrated the importance of the reference when evaluating gains; for example, SmarTrack™ was shown to bring a gain of 4.42% over the baseline settings, which is 2.38 percentage points more than when compared to commissioned settings). This also indicates that Array's typical commissioning practices recover a significant portion of the loss due to slope, although SmarTrack™ allows additional loss recovery.

These same validation cases were also simulated using PlantPredict. The SmarTrack™ gain over commissioned was predicted within 0.5 percentage points at 2.42%, despite using clear sky weather and other modeling simplifications. Combiner-level data indicates that the errors between the predicted and measured gains stem from non-uniform shading of PV strings in a motor block, which are most likely due to row to row height variation in addition to varying slopes within a motor block. We have a new methodology to incorporate the non-uniform shading losses into the modeling calculations, and we will present it in future communication.

The annual gain for this site was also modeled using a TMY weather file. Adjusting for the discrepancy during the validation period, the annual gain is estimated at 1.47%. The potential SmarTrack™ backtracking gain is expected to vary depending on the site topography (higher slope = higher gain) and weather (lower diffuse fraction = higher gain).

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