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White Paper:

TRACKER OPTIMIZATION THROUGH MAXIMUM DIFFUSE IRRADIANCE CAPTURE AND INDIVIDUAL TRACKER TABLE CONTROL

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Executive Summary

As single axis trackers become the commonplace option for utility scale solar power plants in the United States and abroad, tracker OEMs and project owners have worked to optimize the tracking algorithm to maximum energy production. Two functions in particular are being offered by multiple tracker suppliers including GameChange Solar:

- Diffuse irradiance capture, where trackers stow flat on cloudy days.
- Individual tracker table control, where each tracker row rotates at its own schedule based on the elevation of that row relative to the adjacent rows.

Several tracker OEMs have made public statements regarding the extent to which these two functions can increase energy production. As shown in the analysis herein, it is possible for the two functions listed above to be used to increase energy production of a single tracker by roughly 5% over the course of a single day. This aligns with public statements that have been made by other tracker OEMs.

However, it is important that this 5% increase in energy production be put in context. Several tracker OEMs have issued press releases and similar public statements on this topic that could be misleading in that they do not clarify that the calculated increase in energy is only over a single day for a single tracker table at an advantageous elevation to its neighbors, and that the day used to calculate the increase in energy production has a very specific meteorological profile which is not indicative of the weather of a typical solar site over the course of an entire year.

This white paper seeks to clarify the expected increase in energy yield due to diffuse irradiance capture and individual table control over the course of both an ideal day for an ideal tracker and a typical year for a typical solar power plant.

One Day – One Tracker Analysis

As single axis trackers become the commonplace option for Utility scale solar power plants in the United States and abroad, tracker OEMs and project owners have worked to optimize the tracking algorithm to maximum energy production. Two functions in particular are being offered by multiple tracker suppliers including GameChange Solar:

- Diffuse irradiance capture, sold under the brand name WeatherSmart™
- Individual tracker table control, sold under the brand name PowerBoost™

WeatherSmart™ takes advantage of the phenomenon where tracker tables will generate more energy when rotated to flat on fully overcast days. By stowing flat, the panels on the tracker table are exposed to the full hemisphere of diffuse irradiance. If the tracker table were to continue normal rotation under a fully overcast sky, it would cut off the diffuse irradiance from part of this hemisphere from reaching the PV modules and thus reduce power production.

As solar energy becomes more common, the plots of land that are optimal for solar installation are becoming more and more scarce. Solar power plants are now commonly being built on properties with large changes in ground elevation and topography. In these instances, it is optimal for each individual tracker table to rotate on its own schedule of tilt angle vs. time. In particular, in the early morning and late evening, when shadows cast by the trackers are longest,and when anit-shading is in operation, rotating each tracker table at its own tilt angle to account for relative elevation of adjacent tracker tables will optimize energy harvest. The impact of ground elevation on inter-row shading can be seen in **Figures 1A** and **1B** below. Note in **Figure 1A** and the right side of **Figure 1B** where the ground is flat how the shadows on the trackers tables reach the foundations of the tables behind them, while the shadows from the tables on the left hand side of the **Figure 1B**, which are on an upwards slope, stop in the aisle between the tables. By rotating each tracker table on its own schedule, the anti-shading algorithm can be adjusted so each table is as perpendicular to the beam of light from the sun for as long as possible without shading its neighbor.

GameChange Solar has performed analysis utilizing the industry standard engineering software PVsyst to quantify the energy gains from the two functions stated above.

The analysis below is presented for a tracker table in a sample project with a size of approximately 96 MWdc located in North Carolina, USA. The project utilizes 365W modules, a row to row spacing (pitch) of 6 meters and a ground slope of 10% down to the East in this part of the inverter block. Models were created to account for the base case of normal tracker operation, the case where the tracker tables go to a flat tilt on overcast days to calculate the energy gain from WeatherSmart™ and a case with an adjusted row to row spacing to model the backtracking of the trackers when accounting for relative ground elevation to calculate the energy gain from PowerBoost™.

More specifically, this study was conducted using PVsyst as the modeling software and the meteorological data available from Meteonorm. This simulation replicates the ideal weather and topographic conditions required to maximize potential gains using a tracker system with the performance enhancing functions stated above. The methodology used to model the potential benefit of PowerBoost™ was to convert the row to row spacing for a location with a slope elevation of 10% to an equivalent row to row spacing that generated the same length shadows in terms of a flat surface using appropriate trigonometric equations. This resulted in a farther apart row to row spacing for a topographic region of positive slope and a tighter row to row spacing for a negatively sloped region. Using these values that were projected on to a flat surface, four separate analyses were run on PVsyst to maximize potential gains. These were, utilizing a Normal Backtracking with a flat ground row to row spacing, Backtracking with positive elevation row to row spacing, Backtracking with negative elevation row to row spacing, and a case of a flat tracking to replicate stow behavior during a cloudy day. Various outputs were generated using these criteria and corresponding gains were calculated. WeatherSmart™ was assumed to operate on an hourly basis. The percentage gain was calculated by utilizing the total energy production by PowerBoost™ + WeatherSmart™ and the energy generated for a normal backtracking case without any of the above performance enhancing functions.

Figure 1A: Tracker Table Shadows on Flat Ground
(Note each table's shadow reaches the posts of the table behind it)

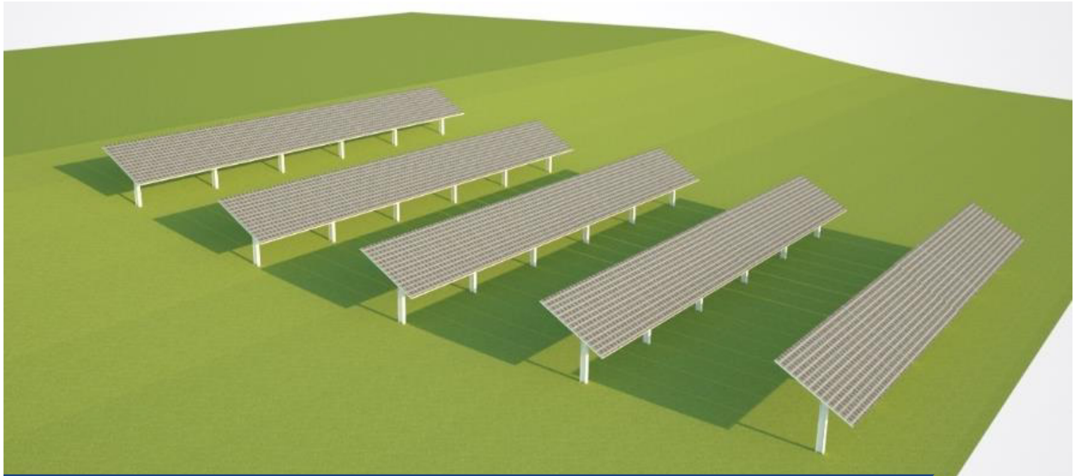

Figure 1B: Tracker Table Shadows on Variable Sloped Ground
(Note the length of the shadow cast by the tables is shorter for tables on the slope)

A day that showcases both of the tracker optimization functions can be seen in **Figure 2** below. The blue line represents the output of a tracker table without either of these functions (the base case). The orange line represents the output of the tacker table with these functions operating. In the morning when the base case tracker table is backtracking using an algorithm accounting for relative elevation of the adjacent tracker tables, the optimized tracker table is more normal to the beam of light from the sun. It is accounting for the fact that the tables on a slope down to the East and therefore can be at a higher tilt (more perpendicular to the beam of light from the sun) without shading the rows behind it. In the middle of the day, the sky turns cloudy. At this time, the tracker table move to a flat tilt where it maximizes the input from diffuse irradiance. At the end of the day, the clouds clear and the tracker table again backtracks, however at this time the table rotates on the same schedule as the base case since the example table is now the controlling table in the array.

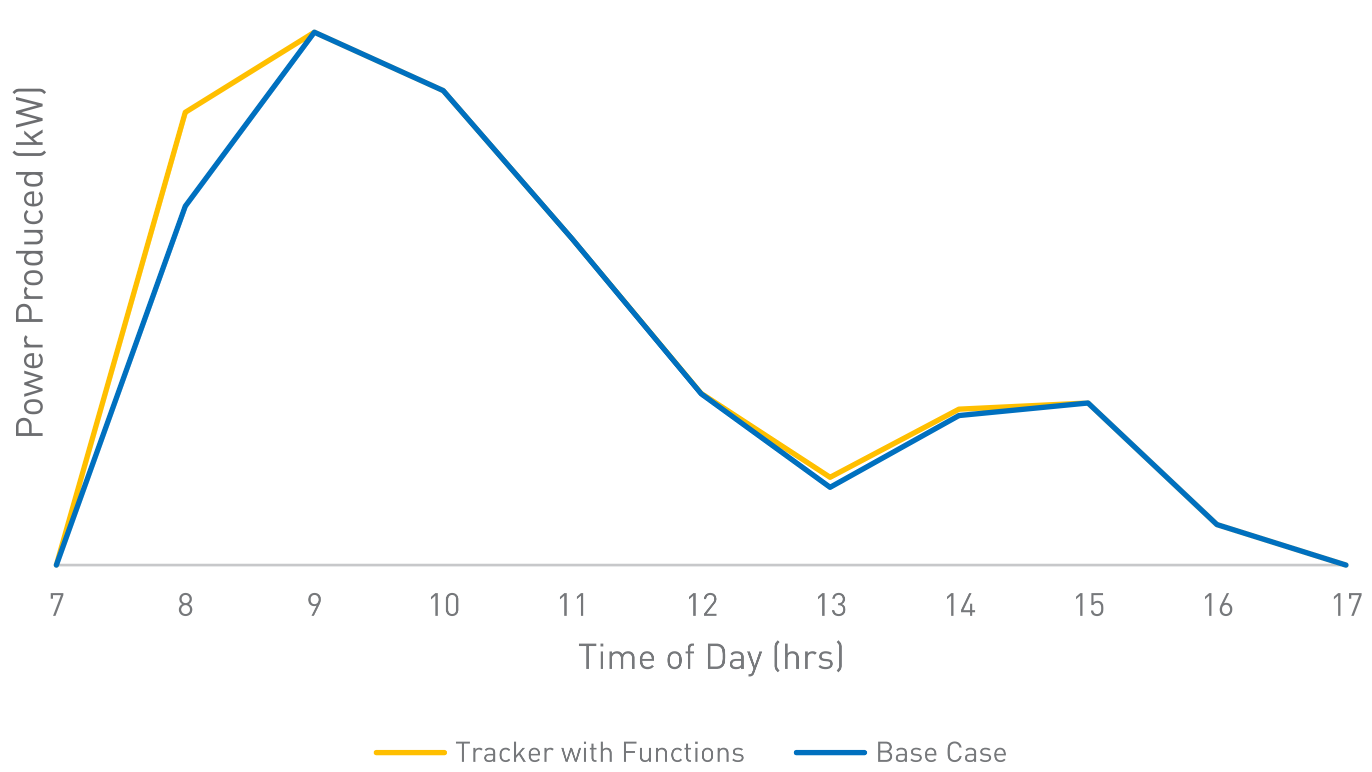

Figure 2: Energy Production through a Day

As a result of maximizing the diffuse irradiance capture and individual tracker control, the example tracker harvests 4.8% more energy over the course of the day.

A few important notes to put this increase in energy production in perspective:

- The analysis above is for an individual tracker table. Not all tracker tables in the solar power plant will be at the same ground slope. Tables on flatter ground will experience smaller increases in energy production due to individual table control.
- The analysis above, and especially the resulting percentage increase in energy production, is based off of a very specific meteorological profile for the amount and type of irradiance that is reaching the modules on the day analyzed. It requires that the site be sunny in the early morning and late afternoon, when advantages of independent tracker operation can be realized, book ending a fully overcast period of time during the middle of the day. It is important to note that during the middle of the day, when the solar power plant is typically operating at maximum output, the sky is assumed to be overcast which results in a lower energy output, even when accounting for stowing flat to maximize diffuse irradiance harvest. The result of this irradiance profile is a relatively low energy harvest throughout the day, yielding a lower denominator for the calculation of percent increase in energy production due to diffuse irradiance capture and individual table control.
- This increase in yield is for a single day only. As typical sites experience 80 or fewer fully cloudy days during the course of the year (roughly 20% or less), the energy production stated above will be diluted. In other words, the percentage increase in energy production over the course of a year due to optimizing the tracker control algorithms for diffuse irradiance capture and individual row operation will be significantly less than what it is on a single day when both of these functions are used in sequence.

Whole Array Annual Analysis

For comparison, the Annual Energy Production analysis for an entire array for the whole year is presented below. This analysis is for the same 96MWdc project in North Carolina, USA that was used in the single day analysis above. The project utilizes 365W modules and a row to row spacing (pitch) of 6 meters, however the topography varies across the site.

Setting up a simulation for quantifying the energy gain for the WeatherSmart™ implementation was achieved using the simulation PVsyst software alongside Meteonorm. The first step was being able to create a criterion for determining what counts as cloud cover. Meteonorm was used to output a csv file with weather data for proposed sites in a format that included:

- Month
- Day
- Hour
- Cloud Cover (Octas)
- Global Irradiance
- Diffuse Irradiance

This format was used to compare the relationship between cloud cover and the ratio between diffuse and global irradiance. Time periods were observed where either the first half or second half of daylight hours had total cloud cover. Total cloud cover was defined as having a minimum average Octa value of 7.75 out of 8, which for an 8-hour window represents at least 6 hours having a complete "8" values and the other being no less than "7". When comparing the ratio of diffuse and global irradiance to time periods which fit the criteria defined for total cloud cover, the ratio was found to be no less than 90%.

A PVsyst simulation used to determine the annual energy production accounted for the following parameters:

- Panel: Jinko JKM 365M-72-V
- Inverter: Siemens Sinacon PV4560
- String size / quantity: 27 / 9730
- Range of Motion: ± 52°
- Pitch: 6 meters
- Losses: PVsyst default values were used
- Backtracking is enabled by default for GameChange Tracker systems and requires a 3D model created in the "Near Shadings" component for PVsyst. For this simulation, a simplified square array was made.

After all the necessary project specific input parameters were set up, two different variants were run for the PVsyst. The first variant specifically uses the range of motion designated for the project. This would serve as the control case to represent normal tracking operation. A second variant was run with the range of motion limited to a flat position (ex: -1° to +1°). This variant represents operation at the WeatherSmart™ flat stow position. The results for the respective variants were output to a csv file with the following parameters:

- Time (Year, Month, Day, Hour)
- Energy injected into Grid (EGrid)
- Global Irradiance
- Diffuse Irradiance
- Sun Angle

During post processing part of this analysis, for each time step, ratio of diffuse irradiance to global irradiance was calculated. To then create a simulated year of tracking with WeatherSmart™ enabled, the outputs of the two simulations were spliced together into a separate combined model, with the default values for each hourly time step being from the control case, and any hour that had an average diffuse/global irradiance ratio above 90% using output values from the restricted ROM variant. The results of these two models are shown in **Figure 3** and **4** below. To compare the simulated effects of WeatherSmart™ implementation, the total production for the spliced case and the control case were compared. Subtracting 1 from the ratio of spliced output and control output shows the percentage gain from implementing the WeatherSmart™ algorithm at the times of assumed cloud cover.

$$\text{WeatherSmart™ Gain} = \frac{\text{WeatherSmart™ Production}}{\text{Normal Production}} - 1 = \frac{166619\ \text{MWh}}{165714\ \text{MWh}} - 1 = 0.55\%$$

For the case of PowerBoost™, additional PVsyst variants were set up with the intention of replicating the tracking behavior of an array built on a slope with a flat array that PVsyst can use. The criteria for determining an equivalent row spacing was to determine at what sun angle do the sloped tables stop backtracking, and finding the larger row spacing for a flat site that results at the same sun angle when backtracking stops.

For sites without individual tracker table control, conservative measures must be taken avoid shading during production hours. In the case of the NC site studied, the average slope across the site was flat, but due to local east-west slopes, the row spacing assumed to calculate the tracking angles was artificially limited by 2'-0" to induce backtracking earlier and avoid inter-row shading in areas with sloping east-west. To understand the effects on production, a PVsyst model was ran with an adjusted row spacing of 5.39 meters and compared to the nominal case. The effect of reducing the row spacing by 2'-0" was a drop in production of 1%.

The adjusted row spacing was then used for the PVsyst model and output to a csv. For each day, the sun angles were compared to the backtracking cutoff angle, and if the sun angle was below, the larger row space variant output was incorporated into the combined model.

Base Case - Balances and Main Results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	73.5	36.87	5.53	96.8	90.8	8510	8404	0.906
February	89.1	41.93	6.56	116.9	110.5	10186	10056	0.897
March	132.5	48.74	11.04	175.7	168.3	14902	14706	0.873
April	166.4	68.53	15.50	217.0	208.1	17794	17572	0.845
May	178.9	85.89	19.87	227.2	217.2	18251	18028	0.827
June	189.0	82.90	23.97	240.2	230.2	19118	18896	0.820
July	187.6	89.77	25.69	235.7	225.4	18649	18433	0.816
August	172.6	79.86	25.53	219.6	209.9	17432	17230	0.818
September	134.6	66.53	21.58	172.2	163.9	13975	13807	0.836
October	112.6	46.94	16.26	149.8	142.5	12538	12383	0.862
November	73	32.89	11.05	97.4	91.7	8316	8211	0.879
December	67.8	29.63	6.72	92.6	86.9	8080	7979	0.899
Year	1577.5	710.47	15.83	2040.9	1945.5	167751	165703	0.847

Figure 3: Base Case Production (6 meter spacing)

Nominal Worst Case - Balances and Main Results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	73.5	36.87	5.53	95.7	89.5	8391	8286	0.903
February	89.1	41.93	6.56	115.5	109.1	10054	9926	0.896
March	132.5	48.74	11.04	174.3	166.8	14760	14566	0.871
April	166.4	68.53	15.50	215.4	206.1	17627	17407	0.843
May	178.9	85.89	19.87	225.3	215.0	18063	17842	0.826
June	189.0	82.90	23.97	238.5	228.1	18948	18728	0.819
July	187.6	89.77	25.69	234.5	223.8	18510	18296	0.814
August	172.6	79.86	25.53	218.2	208.1	17289	17088	0.817
September	134.6	66.53	21.58	170.8	162.2	13837	13671	0.835
October	112.6	46.94	16.26	148.2	140.7	12380	12227	0.860
November	73	32.89	11.05	96.5	90.6	8220	8116	0.877
December	67.8	29.63	6.72	91.0	85.3	7933	7834	0.897
Year	1577.5	710.47	15.83	2023.9	1925.2	166011	163985	0.845

Figure 4: Worst Case Adjusted Production (5.39 meter spacing)

For this particular annual study, WeatherSmart™ was active on a combined 75.5 days out of the year. On days the WeatherSmart™ tracking was active, the average production gain for a single day was 5% (note PowerBoost™ was also active on these days). PowerBoost™ provided a single day average additional gain on top of WeatherSmart™ of 1.17% on days when WeatherSmart™ was active. On a month to month basis WeatherSmart™ and PowerBoost™ contributed about equal amounts to the total gain in production for the site.

Month	Normal Tracking (MWh)	WeatherSmart™ Tracking (MWh)	WeatherSmart™ / PowerBoost™ Tracking (MWh)
1	8405	8461	8544
2	10057	10100	10131
3	14704	14805	14921
4	17572	17654	17817
5	18029	18097	18119
6	18896	19023	19088
7	18434	18518	18536
8	17231	17289	17432
9	13808	13860	13914
10	12384	12472	12560
11	8212	8319	8394
12	7980	8021	8050

Figure 5: WeatherSmart™ + PowerBoost™ Production Comparison by Month

Thus, the percent gain in Annual Energy Production for the entire site on a yearly basis is 1.08% as shown below:

$$\text{WeatherSmart™ / PowerBoost™ Gain} = \frac{\text{Combined Production}}{\text{Normal Production}} - 1 = \frac{167507 \text{ MWh}}{165714 \text{ MWh}} - 1 = 1.08\%$$

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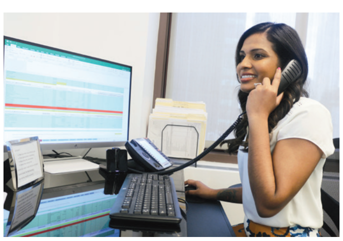

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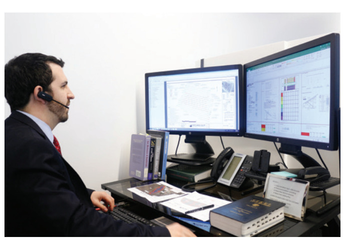

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