Performance of Bifacial Photovoltaic Modules on a Dual-Axis Tracker in a High-Latitude, High-Albedo Environment

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***Abstract* — Bifacial photovoltaic dual-axis tracker systems have the potential to out-perform other module/mounting configurations at high latitudes, where the reflectivity of snow in winter boosts bifacial performance and the low solar angle-of-incidence favors dual-axis tracking. Two years of empirical data from dual-axis experimental systems in Vermont support this assertion, demonstrating that bifacial modules on a dual-axis tracker produced 14 percent more electricity in a year than their monofacial counterparts and as much as 40 percent during the peak winter months. These bifacial gains are *in addition* to the estimated 35-40 percent energy gains of a dual-axis tracker relative to a fixed-tilt system. Such findings suggest that bifacial two-axis tracker systems could be economically attractive in northern latitudes, with high-efficiency modules compensating for the trackers' installation and maintenance costs, and future design improvements enabling further performance gains.**

Index Terms — **albedo, bifacial photovoltaics, design optimization, dual-axis solar trackers, snow**

I. INTRODUCTION

Bifacial solar photovoltaic (PV) modules are rapidly gaining market share [1], a trend driven by multiple studies quantifying the energy gain of bifacial modules relative to monofacial modules (known as bifacial gain) [2,3,]. Bifacial gains can be considerable: estimates range from as much as 30 percent for a fixed-tilt bifacial PV system to 50 percent for a single-axis bifacial tracker (not taking into account a system optimized for all the variables that contribute to bifacial gain, including azimuth, height, tilt angle, cell type, albedo, etc.) In addition, the minimal additional cost for bifacial modules (estimated to be about 3 percent) makes them economically attractive across a broad range of applications [4,5,6].

Recent levelized cost-of-electricity (LCOE) calculations have given the edge to bifacial single-axis tracker systems, which offer tracking gains of roughly 20-25 percent above bifacial gains [7, 8]. But more research is needed to quantify and improve the efficiency, reliability and configuration of bifacial arrays to co-optimize front-backside energy production, both for fixed and tracking systems [9]. Little is known, for example, about the performance of bifacial dual-axis trackers and whether or not these higher-performing systems are functionally and economically competitive with single-axis or even fixed-tilt bifacial systems.

Interest has also begun to focus on large installations of bifacial systems in high-albedo settings [10,11] including both artificial environments, such as white commercial rooftops or enhanced ground substrates, and natural environments, such as deserts and snow-covered terrain [12, 13]. The latter represents an especially attractive market for bifacial PV systems because albedo, which increases the amount of incident light reflected upward, is a primary contributor to bifacial gain [14,15].

This study provides evidence that bifacial dual-axis trackers have a performance advantage in high-albedo operating environments, where the reflectivity of snow favors bifacial PV and the sun's low angle of incidence in winter favors azimuth tracking. What this study does not address are the economics of dual-axis versus single-axis versus fixed-tilt PV systems, such an analysis would have to include equipment and installation costs, lifetime O&M and local electricity rates.

II. OBJECTIVES

Our research aims to identify opportunities to increase the efficiency of PV systems installed at high latitudes where winters are defined by a measurably large amount of snow and relatively low levels of irradiance. The aim of this specific study is to demonstrate the performance of bifacial dual-axis tracker systems in a region that sees snow for five to six months a year, compared with both monofacial modules on the same tracker and an adjacent fixed-tilt bifacial system.[1]. Although more expensive to build and install, dual-axis tracker-systems can deliver energy gains of from 30 to 50 percent above comparable fixed-tilt systems [16]; our intent was to measure the additional energy gain provided by bifacial modules

III. EXPERIMENTAL METHODOLOGY

To quantify the performance potential of dual-axis bifacial systems in snowy climates, we conducted a two-year study of two tracker systems installed for this purpose at the Regional

[1] This effort is part of a larger, three-year project that aims to increase the performance and resilience of PV systems deployed in regions of the U.S. that regularly experience below-freezing precipitation, thus aiding in the adoption, integration and optimal operation of solar resources at northern latitudes.

Test Center for Photovoltaic Technologies in Williston, Vermont.[2] The site, which is located in the greater Burlington area, is at a latitude of 44° 27' and receives an average of 200 centimeters of snow per year, spread over five to six months.

Installed in late 2017, each tracker system was populated with equal numbers of monofacial and bifacial modules, matched by maximum-power output ratings, and mounted in landscape orientation, in five rows of two columns each (see Fig. 1). The trackers were set 60 ft apart to avoid inter-tracker shading and equipped with identical GPS-based, microprocessors programmed to follow the sun's azimuth and altitude. The systems differ, however, in their module technologies (60- vs 72-cell modules), cell types (N-type vs mono-PERC) and also in their backsheet composition (glass vs transparent polyethylene) (see Table 1).

Table 1. Bifacial dual-axis tracker systems at Vermont test site.

Tracker	Strings	Modules	Module/Cell Technology	Max Power
Tracker One	2	10	Monofacial mono c-Si, 60-cell *framed*	290W
		10	Bifacial N-type mono c-Si, 60-cell; glass/glass; *frameless*	290W
Tracker Two	2	10	72-cell mono c-Si monofacial, *framed*	325W
		10	72-cell mono PERC c-Si bifacial, glass/backsheet *framed*	325W

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Fig. 1. Bifacial Tracker Two: 72-cell bifacial modules populate the left half; 72-cell monofacials are on the right. EETS reference cells and tracking error monitors are visible on the lower edge.

As shown in Fig. 2, the upper edge of the tracker platform, sits 18 ft above the ground surface, when the tracker is at a 60° tilt angle, so the difference in elevation between the lower and upper edges may be significant, especially in winter when the platform's tilt angle is greatest. Although not a focus of our investigation, the non-uniformity of backside irradiance as a factor of row height should be investigated.

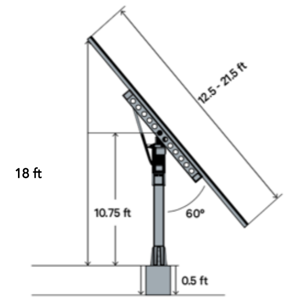

Fig. 2. Schematic of tracker dimensions depicts vertical height of the tracker platform, which adds light to the backside, an amount that increases with tilt angle.

To collect performance data, we instrumented each tracker system as follows:

- Four Omega Type-T thermocouples (two per string), distributed across the back of the array
- Two EETS reference cell irradiance sensors (one for frontside plane-of-array; the other for backside), affixed to the lower edge to facilitate cleaning
- Tripod-mounted albedometer at a height of 1.2m above ground, with horizonal top and bottom pyranometers, to measure ground albedo
- Two tracking error monitors, one with a 120-degree field-of-view (MEMS ISS-D60); the other with a 30-degree field-of-view, which provides greater accuracy (MEMS ISS-D15). The sensors were mounted on the lower edge of the tracker array to facilitate cleaning.
- One string-level DC monitoring box containing Empro current shunts and resistive voltage dividers (both calibrated to an accuracy of 0.1 percent)
- Campbell datalogger configured with an RS485 communications backbone and programmed to collect data every 5-seconds, averaged at one-minute intervals
- Campbell outdoor observation auto-focus camera set at maximum view angle

[2] The Vermont Regional Test Center is no longer operational. Instead, Sandia's northern-latitude PV research is being conducted at Michigan Technical University in Houghton, MI.

Fig. 3. EETS reference cells mounted back-to-back to capture plane-of-array irradiance measurements for the front and back sides of the tracker. The cells were cleaned twice-weekly.

In addition, we equipped each tracker with a dual-port string inverter. The tracker motor was powered by an AC-power source; we made no attempt, however, to measure its power consumption, only its tracking accuracy.

Data from both systems were transmitted via cellular modem to Sandia, where it was monitored on a daily basis for anomalies that might indicate sensor or system failure. During this time, maintenance was minimal: the EETS reference cells and MEMS tracking sensors were cleaned twice-weekly.

To assess tracking accuracy, we collected and analyzed tracking data over the two-year study period. We also removed and EL-imaged modules to look for damage indicative of snow load and/or extreme cold.

IV. Discussion and Results

We collected PV performance data for both dual-axis tracker systems (string-level current and voltage), calculated the bifacial gain for each tracker system and compared energy data from one bifacial string with that of a nearby bifacial fixed-tilt system. We also looked at environmental contributors to performance, including snow accumulation, albedo and shading and also at tracker accuracy. The results suggest that bifacial dual-axis trackers have multiple performance advantages. To quantify these advantages, we divided our analysis into multiple areas of investigation:

A. Annual Power Output

We tracked the monthly power output for both tracker systems (*see Figs. 4 and 5*) for almost two years and compared the performance of bifacial and monofacial strings for each tracker. One-year averages show that:

- Tracker One bifacials (60-cell) produced 14 percent more power than their same-tracker monofacial counterparts;
- Tracker Two bifacials (72-cell) generated four percent more power than their monofacial counterparts, as would be expected given their lower bifaciality.
- Tracker Two bifacials outperformed Tracker One bifacials by less than 2 percent, a minimal amount that reflects their lower bifaciality but higher power rating

Not surprisingly, the Tracker Two 72-cell bifacial modules, which have higher maximum-power ratings, produced more total kWhs in a year than the Tracker One 60-cell bifacials: the two systems had total annual energy production amounts of 8718.1 kWh vs 8314.8 kWh, respectively. But the relatively small difference (< 2 percent) suggests the more efficient bifacial modules are a better economic choice.

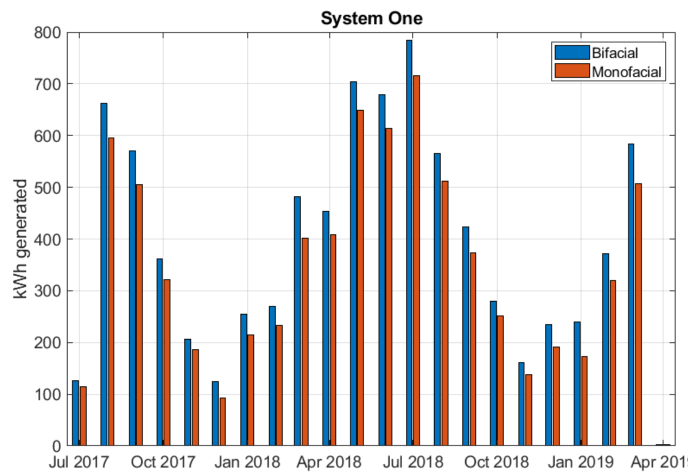

Fig. 4. DC power output for Tracker One is shown here. The bifacial subarray consistently outperforms the monofacial subarray, resulting in a significant increase in energy yield per year

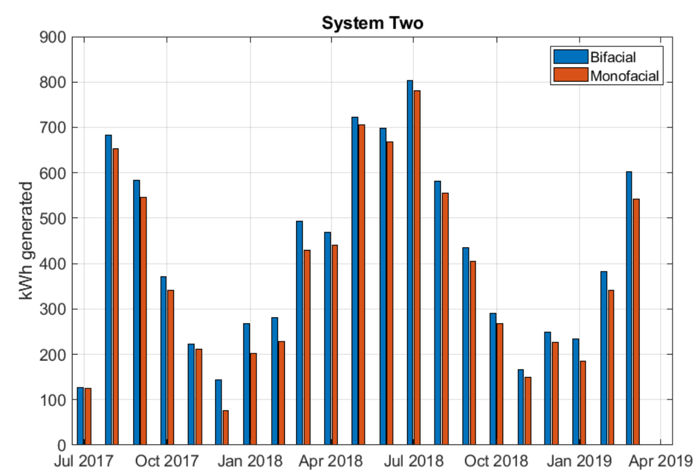

Fig. 5. Tracker Two generated more total kWhs than Tracker One but the bifacial gain is less because of the modules' lower inherent bifaciality.

B. Bifacial Energy Gains

To determine the difference in energy output between the bifacial and monofacial strings on each tracker, and to determine when bifacial gain is greatest, we measured the bifacial gain (BG_E) in energy for each tracker system as a percentage of total energy output, calculated by:

$$BG_E = 100\% \times \left(\frac{\sum_{1month} P_{bifacial} / Pmp_{bifacial}}{\sum_{1month} P_{monofacial} / Pmp_{monofacial}} - \right.$$

where *P* is power and *mp* is the maximum power at standard test conditions. Although the above equation sets a time interval of one month, any unit of time can be calculated.

As expected, the bifacial modules on each tracker outperformed their monofacial counterparts throughout the year, and the gains are greatest in winter when snow cover creates a high albedo. Although bifacial gains vary from year to year and month to month, depending on the age and microstructure of the snow, they are consistently highest in the winter, compensating for otherwise reduced productivity.

Bifacial gains also reflect the inherent bifaciality of the solar cells in each module.. It is important to note the Tracker One bifacial modules have a bifaciality of about 92 percent (they have high-efficiency N-type solar cells), whereas the Tracker Two bifacials have less-efficient mono-PERC cells, and a bifaciality of only 62 percent.

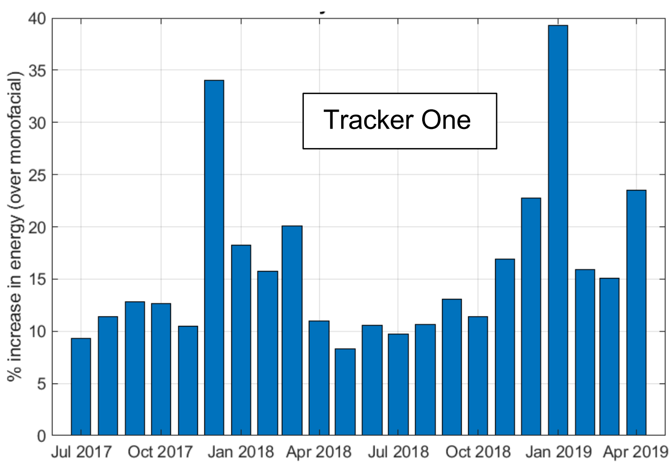

Fig. 6. Bifacial gain for Tracker One. For two consecutive winters (2018 and 2019), the bifacial modules on Tracker One outperformed the adjacent monofacial modules by at least 23 percent.

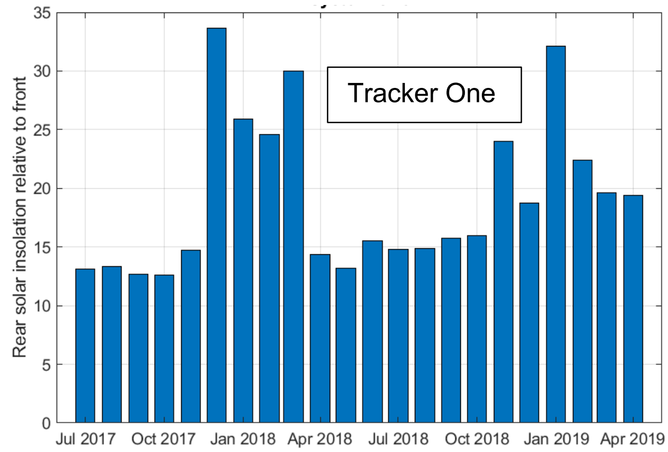

Fig. 7. Measurements of backside irradiance for Tracker One are shown relative to the front side. While the amount of sunlight striking the front is always greater, the difference narrows in winter on account of the reflectivity of snow and snow accumulation on the front side.

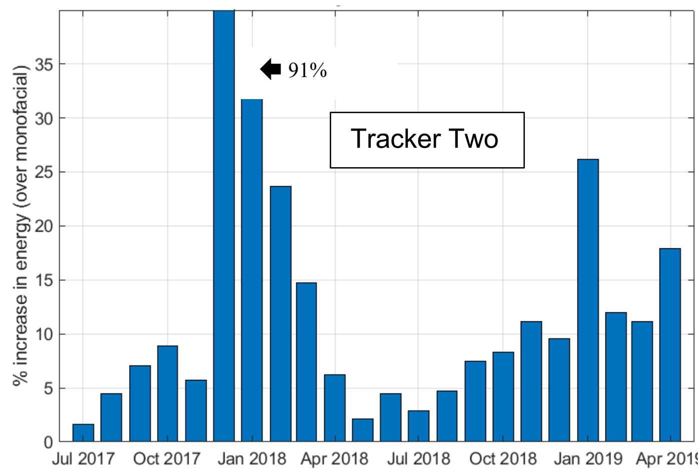

Fig. 8. Tracker Two also shows an increase in bifacial energy production relative to its monofacial subarray. The higher bifacial gain in January of 2018 is likely attributed to snow on the front side, which would block most of the insolation to the front of the array.

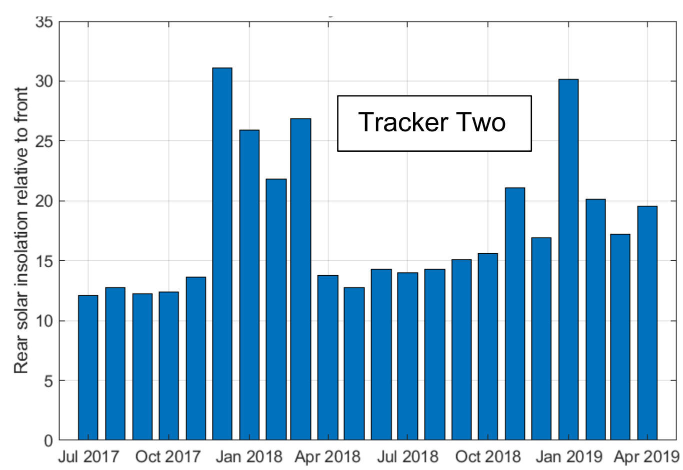

Fig.9. Sunlight striking the backside increases in winter relative to the front but does not correlate directly with energy gain.

In December 2017, Tracker Two had a significant spike—of 91 percent—in bifacial gain (*see Fig. 8*), an increase likely attributable to snow cover that blocks light from entering the front side of the module, but does not affect the rear side, thus accentuating the bifacial gain. A similar spike can be seen for Tracker One in December 2017 but is less intense, likely because snow would have shed more quickly from the frameless modules (*see Fig. 6*).

C. Energy Gains Relative to Fixed-Tilt Bifacial Tracker

We also compared the energy output from the Tracker One bifacial string with an adjacent south-facing, 30-degree fixed-tilt array populated with the same bifacial module technology, normalizing the data for the disparity in maximum power ratings (270w vs 295w frontside-flash.)

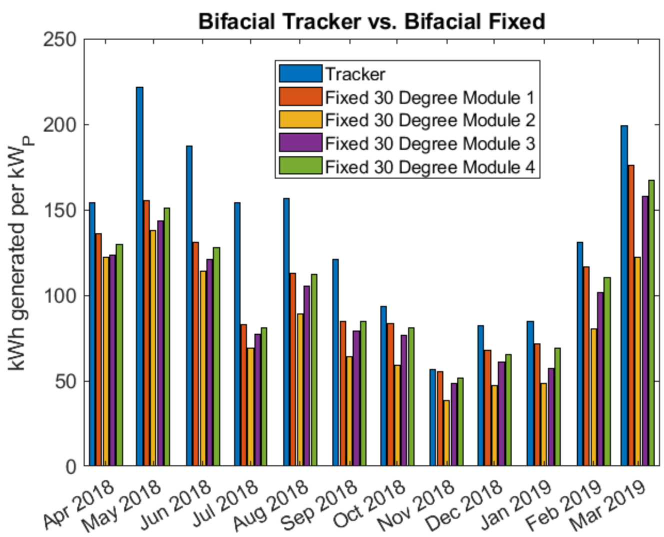

Fig. 10. Energy generated by the bifacial string on Tracker One and adjacent fixed-tilt bifacial modules. The results plotted here were adjusted for maximum power output.

Over the course of 12 months, the tracker bifacial system generated 41 percent more electricity than the fixed-tilt bifacials, with the largest gains in summer when there is more insolation for the trackers to capture, numbers that are consistent with other estimates of dual-axis tracker gains (*see Fig. 10*). Note: the tracker modules connect to a string inverter, resulting in mismatch losses that are reflected in the data, whereas the fixed-tilt modules connect to microinverters and have no mismatch losses.

D. Snow Shedding

Although irradiance striking the backside of bifacial modules is the primary contributor to bifacial energy performance, we documented a second bifacial advantage: snow shed faster from the bifacial half of each tracker (*see Fig. 11*) and fastest from the frameless bifacials. We surmise that scattered irradiance striking the backside is sufficient to warm the bifacial modules, accelerating the snow-shedding process, and that once the

Fig. 11. Time-stamped images of Trackers One and Two demonstrate that the bifacial modules shed snow more quickly than the monofacial modules. Tracker Two (*left*) has framed bifacial modules; the bifacial modules mounted on Tracker One (*right*) are unframed.

dynamics of shedding begin, snow that is not physically impeded by a frame will shed faster. More work is need, however, to quantify the actual snow losses.

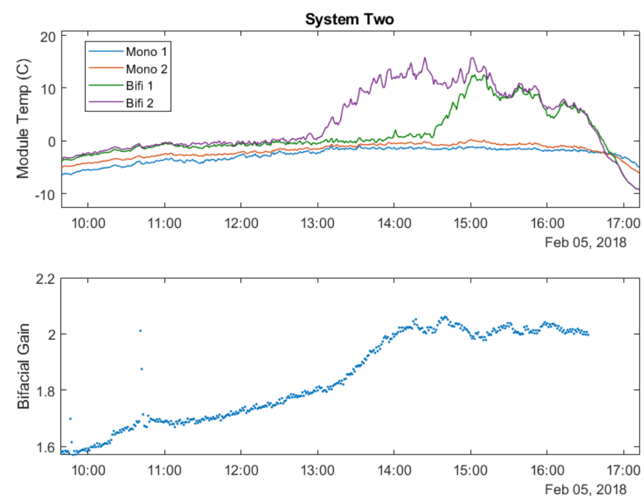

Fig. 12. Back-of-module temperatures (top) and bifacial gain (bottom) are depicted for a 7-hour period in February 2018. As snow slides from the bifacial modules, the difference in back-of-module temperature increases between the bifacial and monofacial modules and bifacial gain increases.

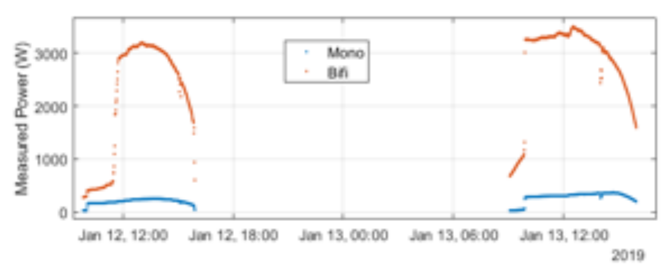

Fig. 13. Data for power output from Tracker One shows that the monofacial modules shed snow 1.75 days after the bifacial modules shed snow, resulting in measurable differences in power production over the course of a long winter.

E. Albedo Measurements

Accurate ground measurements of albedo are key to accurate bifacial performance modeling and are needed to support the widespread deployment of higher efficiency bifacial technologies. Our data shows that albedo ranges from a low of .13 in summer to close to 1.0 in winter (*see Fig. 14*). It is important to note that the albedo ratings above 1.0 are an anomaly attributed to ice and snow buildup on the upper sensor, which would distort the ratio of top-to-bottom sensor readings. Although the pyranometer is cleaned twice a week, ice and snow might persist for 2-3 days.

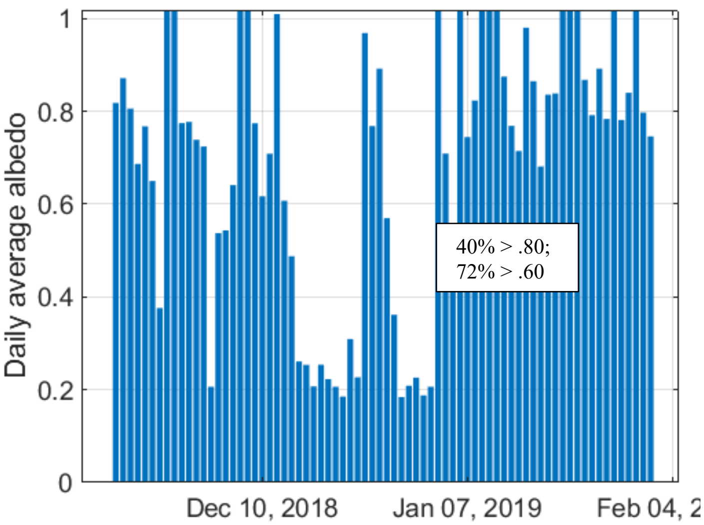

Fig. 14. Winter albedo measurements at the Vermont site. As shown, albedo can range dramatically, depending on changing snow characteristics (compaction, height, age, etc.) and levels of irradiance. Even so, 40 percent of days had albedo measurements above 0.80 and 72 percent exceeded 0.60. Maximum albedo values exceeded 1.0.

Fig. 15. Albedometer at the Vermont test site. The instrument has two horizontal irradiance sensors, one facing up; the other facing down. The bottom sensor is 1.2 m above the ground.

F. Backside Shading from Tracker Frame

The dual-axis trackers chosen for this study were not designed for bifacial modules: they have a large H-shaped support brace and a central pedestal that shades the backside (*see Fig. 10.*) We therefore anticipated that backside shading, and likely scattering from the support trusses, would result in low bifacial gain. Instead, we found that "soft" shading (the offset design of the H frame allows some light to reach the modules' backside) and that, combined with other framing, reduced power output by 1.2 percent for Tracker One and had an even smaller impact on Tracker Two, attributable to the latter's reduced bifaciality and larger 72-cell form factor.

In contrast, the "U" channel creates "hard" shading, that is, almost full blockage of the module behind it, although the amount of area involved is small. We estimate the resulting power loss due to back-of-the-module shading by the U-channel to be 0.4 percent or less. Combining both sources of structural shading, we calculated that total energy lost from backside shading for Tracker One is about 1.6 percent and about 1.1 percent for Tracker Two, percentages that could be further improved by redesigning the trackers for optimal bifacial performance, although we did not conduct the necessary economic analysis, which is left for future work.

Fig. 16. Backside of Tracker One, with DC monitoring box and datalogger mounted on the pedestal. Monofacial modules are on the left side; bifacials on the right. Backside shading proved to have minimal impact on the bifacial gain for this system.

G. Tracker-Error Monitoring

To verify that our results were not skewed by failure of the trackers to accurately follow the sun, we analyzed the tracking performance of both systems by measuring the azimuth error, which is the difference between the trackers' elevation and cross-elevation axes. Cross elevation is defined as the axis in the plane of the tracker face that is orthogonal to the elevation axis. In-plane tracking-error monitors usually measure the elevation- and cross-elevation error. Azimuth error is calculated as:

$$AzimuthError = \frac{CrossElevationError}{cos(Elevation)} \quad (2)$$

Our analysis shows consistent tracking between September 2017 and August 2018, with errors of less than 5 degrees; in addition, no maintenance of the motor or its control system was needed, suggesting—but by no means demonstrating—a relatively robust tracker design.

H. Module Reliability

To ascertain reliability issues that might be uniquely associated with bifacial tracker systems, such as cell cracking initiated by snow load and/or mechanical stress, we subjected 50 percent of the monofacial and bifacial modules n both trackers to electroluminescent (EL) imaging and compared the results with EL images of spare modules kept in storage.

Our preliminary assessment suggests that the glass-glass bifacial modules have fewer cracks than the glass-backsheet bifacial modules but further investigations are needed to be certain and to determine the contributing factors (for example, module size and mechanical stress versus differences in expansion rates for front glass and backsheet.) The cracks also need to be monitored over time and the rates of cracking tied to lifetime estimates for the modules.

I. Other Considerations

Our study did not take into account mismatch losses created by non-uniform backside shading, although we suspect there is less mismatch for dual-axis trackers than for more tightly spaced fixed-tilt or single-tracker systems. We also did not analyze diurnal and seasonal shifts in the reflectivity of snow, which can be affected by angle of incidence, cloud cover, snow compaction and depth, freshness and soiling of the snow, etc. Nor did we add an artificial substrate to boost bifacial gain in non-winter months. In addition, our study fails to consider the economics of dual-axis trackers, which includes the initial cost of installation and lifetime operations and maintenance, nor does it take into account any economic advantages accrued by higher power-output in winter; such analysis is, of course, critical to the long-term viability of bifacial dual-axis trackers, regardless of their performance advantages.

V. CONCLUSIONS

Bifacial dual-axis tracker systems in northern latitudes, which produce significant energy gains over monofacial dual-axis tracker systems in winter, appear to be a viable strategy for reducing LCOE in areas of the world that see persistent snow. Among our most striking findings were gains in average annual energy yields of 14 percent for bifacial relative to monofacial strings on dual-axis tracker systems and gains of 41 percent for dual-axis tracker bifacials relative to fixed-tilt bifacials. These results strongly suggest that dual-axis trackers deployed in northern areas should be preferentially populated with bifacial modules.

Higher performance can be attributed generally to five factors:

1. Ability of two-axis trackers to minimize the angle of incidence, thus maximizing the amount of direct normal irradiance striking the front of the array throughout the year and especially in winter
2. Reflectivity and high-albedo of snow, which is present from four to five months each year in northern regions of the continental U.S. and is continuously refreshed
3. Cooler year-round operating temperatures, which increase operating efficiencies
4. Height of the modules relative to the ground, which increases the amount of light reaching the backside
5. A five-row module platform,which provides a large optical capture area
6. Accelerated snow shedding enabled by 1) backside irradiance that increases module temperature; 2) frameless modules; and 3) high tilt-angle

Our work also speaks to the value of designing systems for their operating environments and to making technological choices based on added performance value. Those choices include:

- *Cell type.* Cells that have a higher inherent bifaciality will deliver a superior performance, especially in winter.
- *Module design.* Frameless modules facilitate snow sliding and therefore shed snow cover faster than framed modules of the same form factor.
- *Tracker spacing.* Neither of our demonstration trackers cast shade on the other, resulting in unimpeded irradiance on both front and back sides.

In conclusion, our work suggests there is an under-recognized opportunity to deploy bifacial dual-axis tracking systems in regions of the world that see abundant snow in winter and are also experiencing significant growth in PV capacity. It is also noteworthy that snow-covered terrain—unlike artificial substrates—adds no additional cost to a project [12, 13], and is constantly refreshed throughout the winter, thus retaining a high albedo for five to six months a year.

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