Investigations of Site-Specific, Long Term Average Albedo Determination for Accurate Bifacial System Energy Modeling

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***Abstract* — In recent years, bifacial modules have been attracting industry interest due to the potential for significant contributions to energy generation from the module rear side. Albedo is a critical parameter needed for modeling rear side irradiation, and accurate albedo values representing both long-term and evolving conditions are needed to quantify the impact of the additional energy generation for financing solar projects. In this paper, the authors identify multiple sources of long-term albedo data and compare to shorter term ground-based measurements in Utah and California. An evaluation of ground-based albedo measurement techniques is presented. Finally, we evaluate methods to reduce higher-frequency measured or long-term albedo data to monthly values commonly needed by industry-accepted software, such as PVsyst.**

***Index Terms* — Solar power generation, photovoltaic systems, bifacial photovoltaics, modelling.**

I. Introduction

Bifacial modules have the potential to be a solar industry disruptor by increasing commercial system yields by 5 to 15%. [1] There is a need for accurate models in order to determine rear side irradiation and also energy gains. One of the most critical inputs for modeling rear side irradiation is long-term average site albedo. [2] To support solar project financing, accurate modeling of bifacial gain for large systems is needed ahead of installation and modeling. The industry is in need of vetted sources and methods for determining long-term average albedo for sites without albedo-enhancing surface treatment. More investigation is needed of available satellite-based albedo sources and how they compare to on-site measurements. [3] In this paper, the authors describe multiple sources of albedo, compare sources to each other and to on-site measurements for one (1) site in Utah and two (2) sites in California, discuss best practices for measuring site albedo, and evaluate variation in modeled rear irradiation for a 20-year dataset on a monthly basis, as well as investigating the impact of multiple methods of collapsing hourly albedo data into monthly values used in modeling software such as PVsyst.

II. Long-Term Albedo Sources

The National Solar Radiation Database (NSRDB) incudes estimates of surface albedo derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua satellites and the Integrated Multisensor Snow and Ice Mapping System [4]. The data is delivered at 4 sq-km resolution and is available 1998-2015, which presents several limitations. First, changing land use, for example clearing vegetation in preparation for installation of a solar PV plant, means that historical averages may not be representative of the current or expected albedo. Second, the spatial resolution may be too coarse to be representative of the area of interest. A more recent, more precise database is therefore desirable. Such a database would allow comparison to ground based sensors being deployed by parties interested in studying bifacial PV.

Other potential sources for surface albedo, such as NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) have not been designed or validated for PV modeling. MERRA-2 has a resolution of approximately 50 sq-km.

SolarAnywhere® is a thoroughly validated source for long-term and real-time solar irradiance data [5]. Clean Power Research and research partners at SUNY Albany have developed a new experimental algorithm to estimate albedo that is suitable for PV modeling leveraging existing SolarAnywhere infrastructure. Observations from geosynchronous satellites are used to create a surface albedo history which is augmented by snow data from the Snow Data Assimilation System (SNODAS). Since the data can be generated from 1998 through trailing month and at 1-km-sq spatial resolution, the new data has potential to address the limitations of existing sources.

III. Ground Measured Albedo

High-quality, well-maintained ground-measured irradiance is commonly used to qualify satellite irradiance data [6,7]. The authors wanted to explore application of similar methods for qualification of satellite albedo data. A pyranometer-based albedometer was used to measure albedo noting that satellite albedo outputs are broadband, PVsyst references a pyranometer-based albedometer for measurement of the "Albedo Coefficient," and albedo measurement using pyranometers is an approved method per the World Meteorological Organization (WMO) [4,8,9].

A. Instrumentation & Scheduled Maintenance

The SRA20 was used to measure broadband (285 to 3000 x 10^{-9} m) albedo at all locations [10] and consists of two ISO

9060 secondary standard pyranometers. A CR1000 datalogger [11] was used to measure analog output signals, apply manufacturer temperature correction and control dome heaters to suppress dew and ice. Albedometers were cleaned and leveled weekly at both CA sites and five days per week (Monday through Friday) at the Utah site.

B. Instrument Siting

WMO siting recommendations were followed to minimize the influence of nearby objects such as reflections or shading. Albedometers were mounted on a low-profile tripod distanced 30 meters from the closest obstruction. Each sensor was mounted at the end of a 1.5-meter boom arm that was oriented true south toward the equator. Each sensor was positioned with its center line 1.5 meters above the ground surface. A short-term test was conducted to observe the effect of sensor mounting height on measured albedo. Albedo was measured at three heights 1.0, 1.5, and 2.0 meters for 1 hour each on a clear sky day at the Utah site on June 7, 2018 over uniform native vegetation. Albedo was found to be 0.223, 0.223, and 0.221 respectively.

C. Data Filtering

Other researchers have reported on the challenges of measuring albedo and the requirement for data post-processing [12]. A simple data filter was used to remove ground-measured albedo values less than 0 and greater than 1. Values recorded when the solar zenith angle was less than 10 degrees were also removed to minimize angle of incidence (AOI) and pyranometer angular response error effects (Figure 1).

Fig. 1. Sample day of ground-measured albedo data in Utah, before and after filtering

IV. Comparison of Ground Measurements to Satellite

Ground-based measurements were made every three-seconds and one-minute data was compared to long-term satellite data sources for three sites: two in California, Site A and Site B, and one in Utah. Ground-measured data were filtered as described above and averaged for the hours around solar noon to give a daily value comparable to the isotropic albedo anticipated by common PV modeling tools such as PVsyst [13]. Time series data comparisons of daily average ground-based albedo measurements to daily averages derived from the various satellite sources are shown in Figure 2. Since recent data from the NSRDB are not available, average daily values for the period 1998-2015 were used.

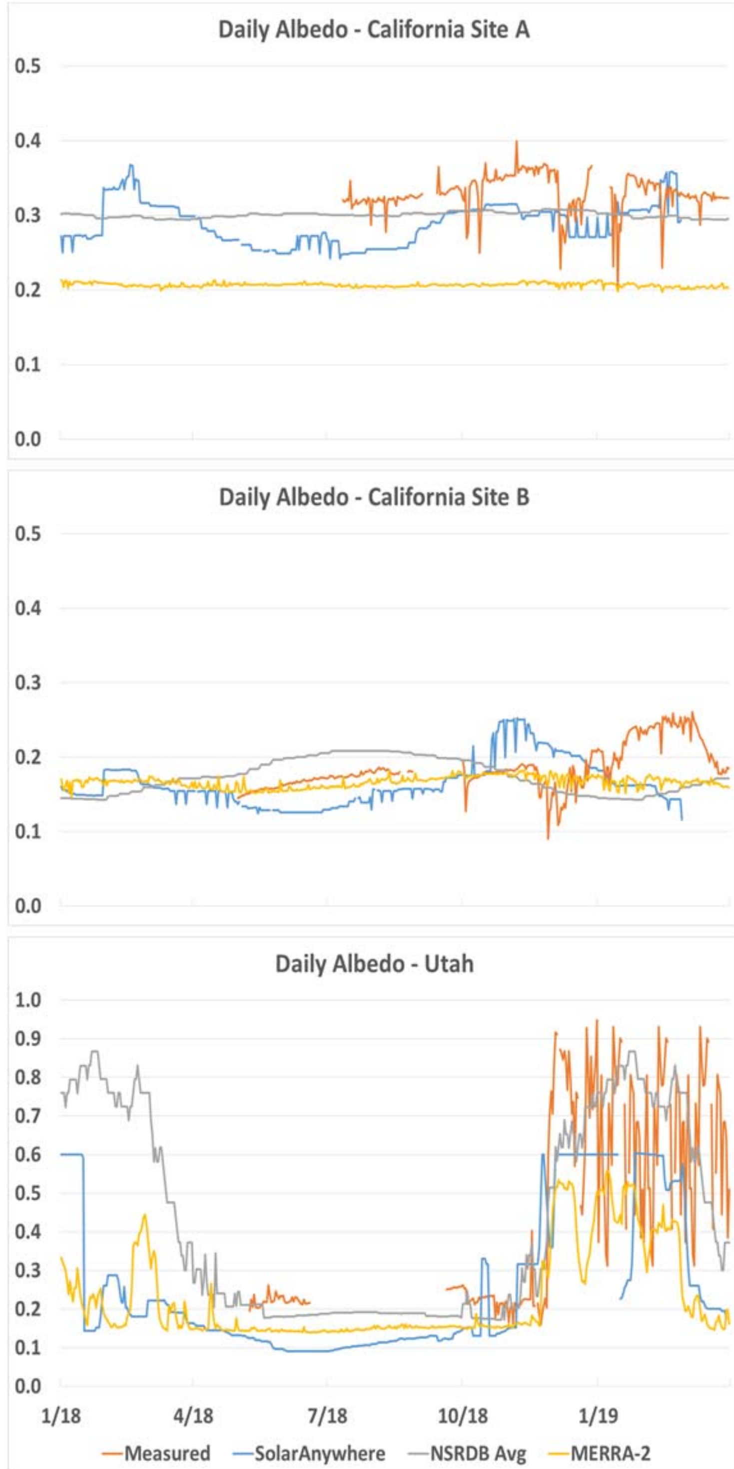

Fig. 2. Comparison of avg. daily albedo from four sources at three locations.

California Site A is located on sparsely-vegetated sand and exhibits an average measured albedo of 0.33. Site B is located on a grassy plain with historic use as farmland and has a lower albedo of 0.19. The Utah site is in an open field with variable low vegetation and shows the impact of ground snow cover, with December albedo averaging 0.78.

Taking ground data as the reference, monthly mean absolute error (MAE) is calculated to understand how well the remote sources correspond to ground measurements. Monthly averages were chosen since monthly albedo is typically used for PV modeling. The all-month MAE for the SolarAnywhere, NSRBD average, and MERRA-2 albedo data are 0.06, 0.04, and 0.09 respectively. These compare favorably to a standard albedo assumption of 0.2, which has an MAE of 0.12.

While the monthly errors for the NSRDB and SolarAnywhere sources are reasonably low, inspection of the data reveals periods of poor correlation between the remote sources and ground. This may be explained by the spatial resolution of the sources. While an albedometer measures the albedo of the surface immediately surrounding the sensor (an area tens of meters in diameter depending on the height of the sensor), the remote sources described here capture 1-50 sq-km.

Consider for example November through March at Site B where there is no apparent correlation between the remote sources and the ground data. Site B is surrounded by farmland. Satellite photography shows a patchwork of fields, each a different color (and presumably albedo) and changing throughout the year. Each source is measuring a different, overlapping area, which helps explain how the measurements can diverge.

Similarly, the Utah site is adjacent an urban environment. The remote sources are influenced by the surrounding buildings and roads while the ground sensor is not. In addition, snow cover is likely to be highly variable.

Site A has the best overall correlation between the NSRDB, SolarAnywhere and the reference. Perhaps not coincidentally the site is in a desert with little variation regardless of spatial resolution.

The data presented here emphasize the importance of considering the spatial resolution and period of the albedo data source when using the data for pre-construction resource assessment. The historical and current surface of the site, especially when viewed with a course spatial resolution, may or may not be representative of the post-construction surface condition, which is ultimately what influences energy production.

V. Monthly Values for Modeling

Common industry software for modeling system-level bifacial energy output allows for monthly resolution of albedo values, whereas long-term sources and on-site data provide daily, hourly and sub-hourly data resolution. Methods for determining “typical long-term average monthly albedo” and for collapsing high resolution on-site and satellite albedo data into monthly values are needed for energy modeling. Canadian Solar has published an open source modeling software, CASSYS [14], which allows for user input of high resolution (sub-hourly, depending on climate file resolution) albedo values. The authors used CASSYS to evaluate variation in bifacial irradiation gain due to monthly albedo variation and also to evaluate different methods of determining representative monthly albedo from hourly resolution data.

Using 20 years (1998-2017) of satellite-based Solar Anywhere weather data and concurrent albedo data provided by CPR, NSRDB and MERRA-2 we investigated the impact of different albedo sources and resolution on modeled rear irradiation. CPR and NSRDB albedo data were provided in daily resolution and daily and monthly albedo values were compared. MERRA-2 albedo was provided with hourly resolution and was evaluated in 4 ways: hourly albedo, average noon-time values for a given month and year, the arithmetic average of albedo values between 10 am and 2 pm for a given month and year, and the irradiance-weighted average of albedo values between 10 am and 2 pm for a given month and year. Gains reported represent the sum of hourly rear irradiation divided by the sum of hourly front-side plane of array irradiation for a given month.

Eight sets of simulations were run at 3 locations: California Site A, California Site B, and Utah. The base case PV system configuration used was a backtracking 1-portrait horizontal single axis tracker at 0.29 ground coverage ratio (GCR), hub height of 1.5 m and rotation limits of 52 degrees.

One additional set of 8 simulations was run at the Utah site. The authors selected the Utah location for further investigations since the variation in albedo (both inter- and intra-source) was greatest there. The alternate case PV system configuration used was 2-portrait 25 degree fixed tilt racking at 0.5 GCR, ground clearance of 1.5 m and azimuth of 0 degrees (due south).

We show that for a horizontal single axis tracker at the Utah site, the error introduced by different methods of reducing data to monthly inputs is not material. In contrast, the error introduced by different sources of albedo can be significant for a given month particularly in snowy regions. We also show that monthly variation, particularly in snowy months, can be significant. Results are shown in Figures 3-6. Note the different scales on the y-axis between the sites.

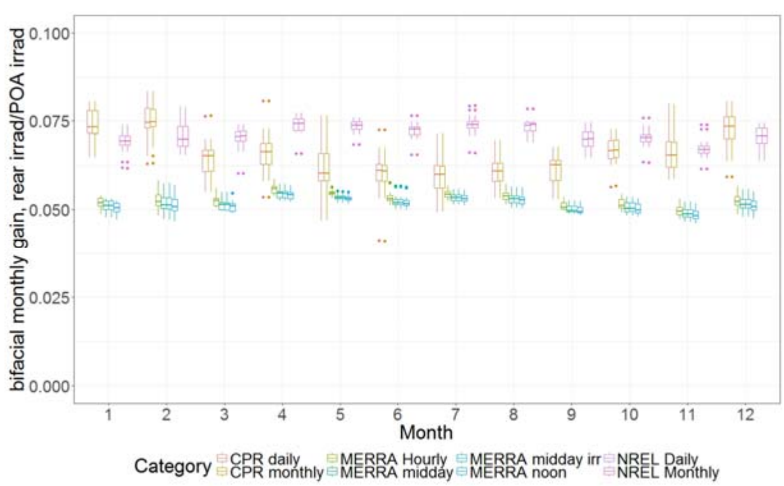

Fig. 3. Comparison of SAT bifacial gain by month at California Site A for 3 sources of concurrent albedo data via multiple methods of collapsing albedo data

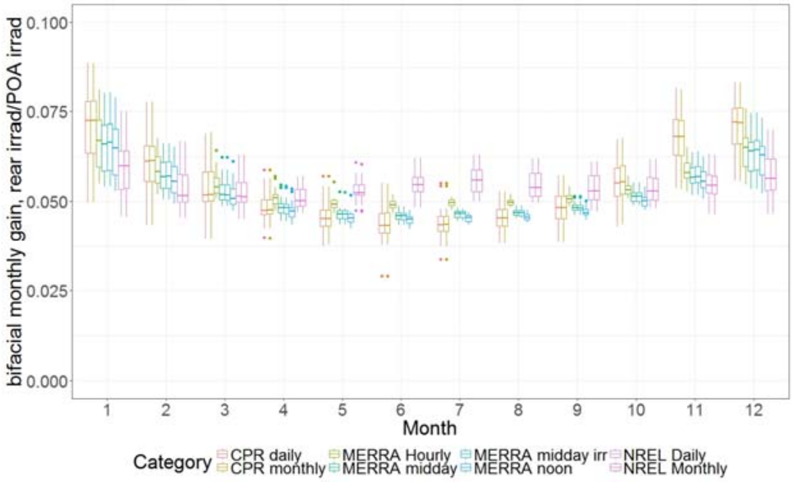

Fig. 4. Comparison of SAT bifacial gain by month at California Site B for 3 sources of concurrent albedo data via multiple methods of collapsing albedo data

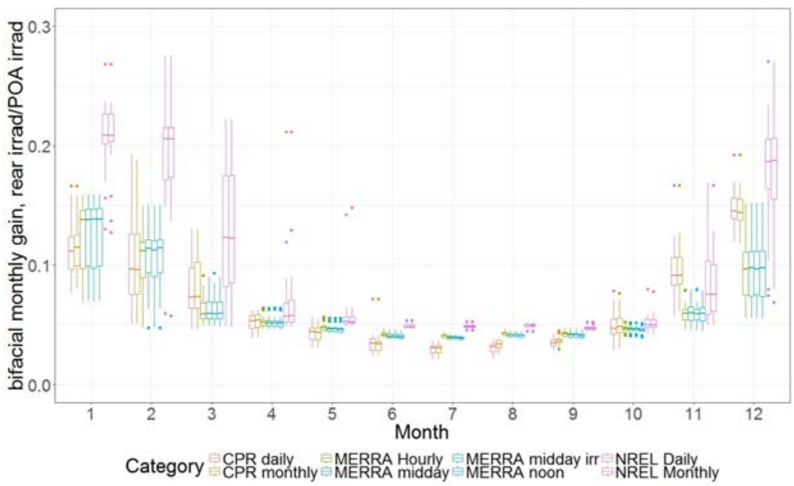

Fig. 5. Comparison of SAT bifacial gain by month in Utah for 3 sources of concurrent albedo data via multiple methods of collapsing albedo data

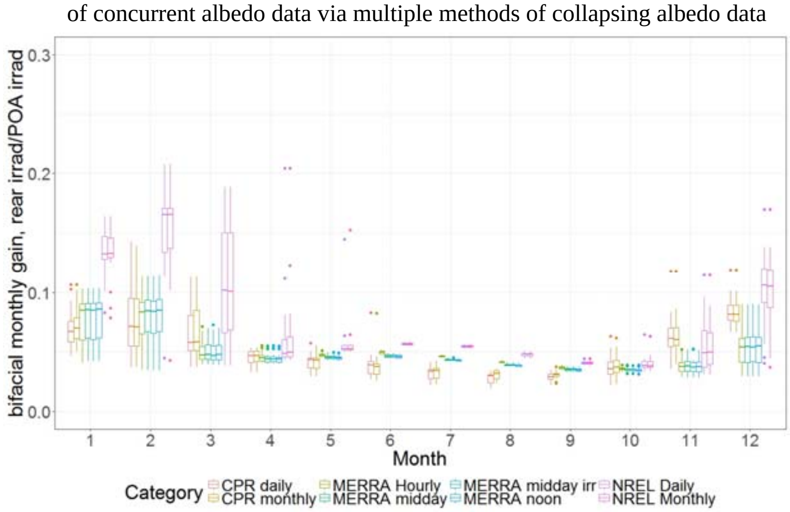

Fig. 6. Comparison of FT bifacial gain by month in Utah for 3 sources of concurrent albedo data via multiple methods of collapsing albedo data

An evaluation of the impact of the temporal albedo variations on annual dc energy for the SAT Utah is shown in Figure 7. This was calculated by taking the monthly rear irradiation value and dividing by the sum of the annual rear irradiation and front-side plane-of-array irradiation. This particular case was selected as the highest value and variation in monthly gain was shown in Figure 5 of the four boxplots above. The scale of the y-axis in Figure 7 has 0.5% major intervals. Once again, the largest impacts are seen in the source to source variations rather than the albedo interval or collapsing methods. Disregarding the NSRDB March results, the inter-annual variability on annual energy is generally less than about 0.15% per month in winter and less in summer months. For March, NSRDB shows variations approaching 0.3% per month, when the limits of the upper and lower quartile are reviewed.

The authors also investigated the time of day dependence of bifacial irradiation gain on albedo. For example, using a horizontal single axis tracker at our Utah site, front side plane of array irradiation, and rear irradiation using 2-4 different albedo methods for the 3 sources are show in Figure 8 on December 22, 2000 and June 24, 2000. The days were selected as representative clear days for summer and winter. For the single axis tracker system at the Utah site, looking only at the simulations using MERRA-2 albedo data, for these two days we found winter rear irradiation modeled using hourly albedo values were approximately 40% higher than simulations of rear irradiation using monthly albedo values in all hours, and in summer, rear irradiation modeled using monthly albedo values was approximately 15-60% lower in the hours during the shoulders of the day when compared to simulations of rear irradiation using hourly albedo values. Nonetheless, these differences introduced less than a 2.7% impact on daily energy in winter and 0.2% impact on daily energy in summer. Comparing source to source, for these two days we found winter rear irradiation modeled using NSRDB albedo values were approximately 100% higher than simulations of rear irradiation using MERRA-2 albedo values, and in summer, rear irradiation modeled using CPR albedo values were approximately 20-90% lower on an hourly basis when compared to simulations of rear irradiation using NSRDB albedo values. These differences introduced 8.4% impact on daily energy in December and 1.2% impact on daily energy in June. Thus, once again the impact of the differences from different albedo sources has significantly more impact on energy than does the granularity of data used within a single source. However, when considered in the context of annual energy, the impact of the differences is generally less than 0.15% per month, as was shown in Figure 7.

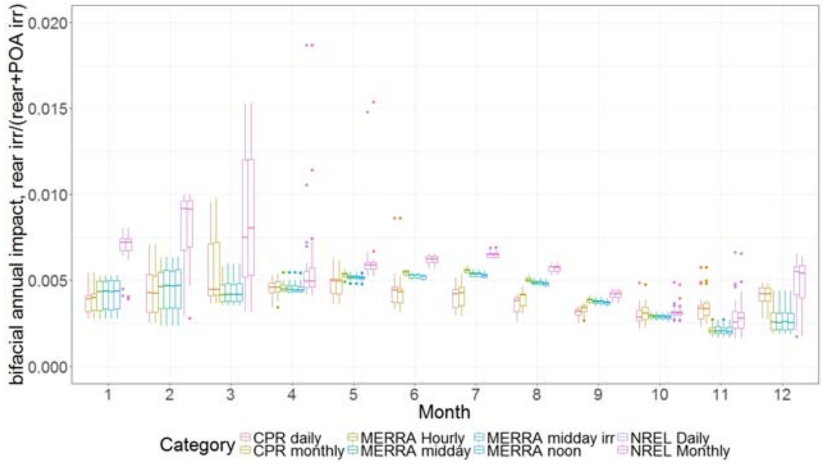

Fig. 7. Comparison of SAT annual dc energy impact of bifacial gain by month in Utah for 3 sources of concurrent albedo data via multiple methods of collapsing albedo data

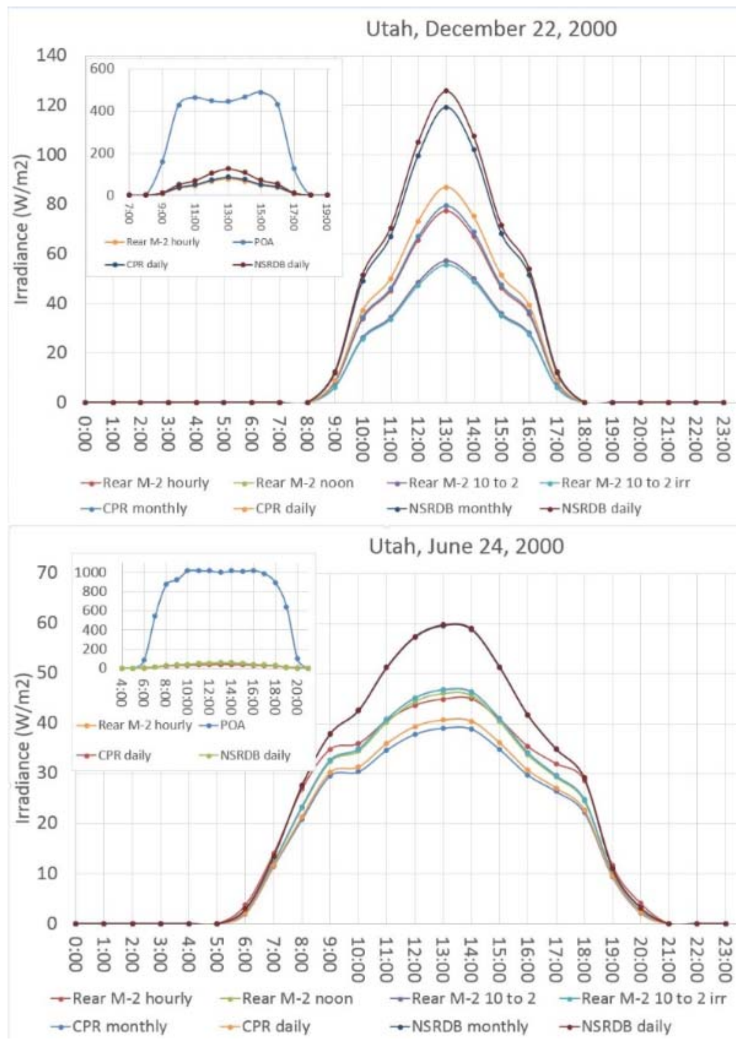

Fig. 8. Front and rear irradiation (calculated from 4 different albedo methods) for single axis tracker in Utah for clear days in December and June.

Simulations were also performed on measured meteorological and albedo data for the Utah site. The period of measure was from 11/2/2018 through 5/31/2019. Global horizontal irradiance, diffuse horizontal irradiance, ambient temperature, wind speed and albedo were collapsed to hourly resolution and input into the CASSYS model. Six hours of meteorological data were missing on 4/10/2019, and four hours were missing on 5/8/2019. These were filled in from surrounding data at similar conditions and represent less than 0.3% of the total irradiation of the data set. For the 7 months represented by the measured data, Table 1 shows monthly gain versus the maximum and minimum gain for each modeled data source. Maximum and minimum for CPR and NSRDB datasets were pulled from the simulations using daily albedo resolution. Maximum and minimum for MERRA-2 datasets were pulled from the simulations using noon-time albedo values. All values of gain due to rear irradiation that were modeled using the measured meteorological and albedo data were within the extremes represented by the models using the NSRDB albedo dataset. Four out of seven months (December 2018, January 2019, February 2019, and May 2019) showed slightly higher gains than the maximum value modeled using the CPR and MERRA-2 albedo datasets. This is an expected result, given that Figure 2 showed the measured albedo data generally exceed both the MERRA-2 and CPR modeled values during the concurrent time period.

VI. Conclusion

This paper addresses the industry need for bankable albedo inputs for accurate bifacial modeling. We reviewed several sources of long-term albedo, compare to on-site measurements, and review impacts on modeling rear irradiation using different albedo resolutions. Results show that monthly resolution for albedo inputs is an acceptable resolution for minimal impact on uncertainty of bifacial system energy modeling. Further effort is needed for deeper review of long-term sources, spatial variability, and the potential value-add from tuning satellite sources to on-site measurements.

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TABLE I

COMPARISON OF GAINS FROM MODELED AND MEASURED SOURCES BY MONTH

	CPR		MERRA-2		NSRDB		Measured Met Data
Month	Max	Min	Max	Min	Max	Min	
1	16.7%	7.6%	15.9%	7.0%	26.8%	13.0%	20.6%
2	19.3%	5.0%	15.0%	4.7%	27.5%	5.9%	19.5%
3	13.0%	4.5%	9.0%	4.8%	22.2%	4.9%	5.4%
4	6.2%	3.8%	6.4%	4.5%	21.2%	4.8%	5.4%
5	5.6%	3.0%	5.5%	4.2%	14.2%	4.9%	6.3%
6	7.1%	2.4%	4.5%	3.7%	5.4%	4.6%	
7	3.6%	2.1%	4.1%	3.6%	5.2%	4.5%	
8	3.7%	2.1%	4.4%	3.8%	5.2%	4.4%	
9	4.2%	2.8%	4.6%	3.7%	5.2%	4.4%	
10	7.8%	2.8%	5.1%	4.0%	8.0%	4.2%	
11	16.7%	5.6%	7.8%	4.4%	16.9%	5.0%	5.8%
12	19.2%	12.0%	15.2%	5.5%	27.1%	7.4%	21.1%