Albedo Data Sets for Bifacial PV Systems

Preprint

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Albedo Data Sets for Bifacial PV Systems

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***Abstract*—For use by the PV and financial communities to better estimate the performance and to reduce the risk of bifacial PV systems, data sets of ground albedo and associated meteorological data were developed by using existing measurement network data and data contributed by the PV industry. The data sets include time-series data as well as summary information of tabular monthly and yearly data and plots of monthly and hourly albedo values. Complete information is presented in a user's guide and data are available for download from NREL's DuraMAT website.**

***Keywords*—Albedo, bifacial, irradiance, data, network.**

I. Introduction

For mono-facial photovoltaic (PV) systems, the ground-reflected radiation typically comprises only 1% to 2% of the total radiation received by the PV module. Consequently, a rudimentary understanding of the ground albedo is adequate for predicting their performance. However, for bifacial PV modules where their benefit is determined by the additional radiation reflected by the ground to their backside, a better understanding of albedo values and characteristics is needed by both the PV and financial communities to better estimate performance and to reduce risk. This was identified as a key need at the 2018 Bifacial PV Workshop. Subsequently, the Department of Energy (DOE) initiated work with the National Renewable Energy Laboratory (NREL) to provide albedo data for different locations and ground surfaces for both the simulation of bifacial PV systems and for summary information, including variations in albedo with respect to time of day, season, and year.

Albedo is the fraction of the incident sunlight that the surface reflects. It is not a constant for a surface because it varies with the spectral and angular distribution of the sunlight. These variations result from a changing sun position due to time of day, season, and latitude, and whether it is cloudy or sunny.

Except for ice, snow, and water, most surfaces exhibit an increase in albedo for wavelengths greater than about 700 nm [1]. Consequently, it is typical for early morning and late afternoon hours to have slightly greater albedos than for midday because the distribution of the solar spectrum shifts to longer wavelengths for these times. Additionally, the albedo may increase because the incidence angle of the solar radiation to the surface is increased.

The condition of the surface also influences the albedo. Dry soils have a greater albedo than wet soils and dry vegetation has a greater albedo than green vegetation (green vegetation uses the radiation from 400 nm to 700 nm for plant growth). Surface roughness is also a factor with rougher surfaces having lower albedos because of increased self-shading.

For the data sets assimilated for this work, albedo measurements are made with albedometers consisting of two horizontal pyranometers, one facing the sky and the other facing the ground. The albedo is the irradiance measured by the ground-facing pyranometer divided by the irradiance measured by the sky-facing pyranometer. The conventional name for the sky-facing measurement is the global horizontal irradiance (GHI). For consistency, we refer to the ground-facing measurement as the ground-reflected irradiance (GRI). Elsewhere, the GHI and GRI may be referred to as the downwelling and upwelling (reflected) irradiances, or the incoming and outgoing (reflected) irradiances.

Besides GHI and GRI, other meteorological data useful for determining the performance of PV systems are included in the data sets, if available. This includes the direct normal irradiance (DNI), the diffuse horizontal irradiance (DHI), the dry bulb temperature (Tdry), the relative humidity (RH), the wind speed (Wspd), the wind direction (Wdir), the atmospheric pressure (Pres), and accumulated precipitation (PrecipAccum).

The albedo data sets include data from the Surface Radiation budget (SURFRAD) and AmeriFlux measurement networks and data provided by Canadian Solar, Inc. and SunPower Corporation. The SURFRAD network consists of seven stations and is operated by the National Oceanic and Atmospheric Administration (NOAA) to provide continuous and high-quality surface radiation budget measurements to support climate research, weather forecasting, satellite, and educational communities [2].

The AmeriFlux network data are contributed by individual scientists that operate measurement stations in North, Central, and South America for the purpose of measuring ecosystem CO2, water, and energy fluxes. Most of the sites are in the U.S., followed by Canada. The AmeriFlux network is managed by the Lawrence Berkeley National Laboratory with funding from the U.S. Department of Energy's Office of Science. For complete information, see the AmeriFlux website [3]. The AmeriFlux network is intended to represent major climate and ecological biomes, including tundra, grasslands, savanna, crops, and forests. We used a subset of 28 stations with ground covers that might be present for PV installations (grasslands, deserts, low brush or crops; no forests or wetlands) and that had the required measurement of albedo.

TABLE I. LIST OF MEASUREMENT STATIONS

StationID	**Location**	**Data Source**	**Data Years**	**Ground Surface**	**Overall Albedo**
BondvilleIL	Bondville, IL, USA	SURFRAD	24	Native grasses	0.247
BoulderCO	Boulder, CO, USA	SURFRAD	23	Sandy with exposed rocks, sparse grass, desert shrubs, cactus	0.199
DesertRockNV	Desert Rock, NV, USA	SURFRAD	20	Fine rock and scattered creosote bush	0.211
FortPeckMT	Fort Peck, MT, USA	SURFRAD	23	Native grasses	0.247
GoodwinCreekMS	Goodwin Creek, MS, USA	SURFRAD	24	Pasture grass and sparse deciduous trees	0.200
PennStateUnivPA	Penn State Univ, PA, USA	SURFRAD	20	¾ grass and ¼ crops	0.252
SiouxFallsSD	Sioux Falls, SD, USA	SURFRAD	15	Native grasses	0.238
ChangshuJiangsu	Changshu, Jiangsu, China	Canadian Solar, Inc	1.3	Concrete White-painted concrete	0.236 0.533
WuhaiInnerMongolia	Wuhai, Inner Mongolia, China.	Canadian Solar, Inc	1.1	Desert sand with wheat grass squares	0.282
DavisCA	Davis, CA, USA	SunPower Corp.	0.8	Gravel, light to medium gray White tarp	0.145 0.568
LethbridgeAlberta	Lethbridge, Alberta, Canada	AmeriFlux	1	Mixed grass prairie	0.250
MedfordOK	Medford, OK, USA	AmeriFlux	3	Hay pasture	0.211
WoodwardOK_1	Woodward, OK, USA	AmeriFlux	4	Switchgrass	0.186
WoodwardOK_2	Woodward, OK, USA	AmeriFlux	4	Switchgrass	0.204
AudubonRanchAZ	Audubon Research Ranch, AZ, USA	AmeriFlux	10	Native grasses	0.217
BouldinCA	Bouldin Island, CA, USA	AmeriFlux	3	Alfalfa	0.221
BrookingsSD	Brookings, SD, USA	AmeriFlux	7	Pasture grass	0.262
CanaanValleyWV	Canaan Valley, WV, USA	AmeriFlux	6	Grassland	0.294
CorralPocketUT	Corral Pocket, UT, USA	AmeriFlux	7	Semi-arid grassland with 38-80% bare ground from livestock grazing	0.238
CottonwoodSD	Cottonwood, SD, USA	AmeriFlux	4	Grassland	0.181
DiabloCA	Diablo, CA, USA	AmeriFlux	3	Grassland	0.206
DukeFieldNC	Duke Field, NC, USA	AmeriFlux	5	Tall fescue grass mowed annually	0.203
FlagstaffAZ	Flagstaff, AZ, USA	AmeriFlux	6	Post forest fire grasslands	0.219
FermilabIL	Fermilab – Batavia, IL, USA	AmeriFlux	14	Prairie grass	0.221
FieldStationKS	Kansas Field Station, KS, USA	AmeriFlux	8	Grassland	0.193
KonzaPrairieKS	Konza Prairie, KS, USA	AmeriFlux	6	Grassland	0.190
TurfgrassFieldMN	Turfgrass Field, MN, USA	AmeriFlux	4	Turfgrass lawn	0.322
ReynoldsCreekID_1	Reynolds Creek, ID, USA	AmeriFlux	3	Low sagebrush	0.179
ReynoldsCreekID_2	Reynolds Creek, ID, USA	AmeriFlux	3	Mountain big sagebrush	0.231
RosemountMN	Rosemount, MN, USA	AmeriFlux	5	Grassland	0.247
SonoranDesertCA	Sonoran Desert, CA, USA	AmeriFlux	7	Desert	0.245
SouthGrasslandCA	Southern Californian Grassland, CA, USA	AmeriFlux	9	Grassland	0.165
McKenzieFlatsNM	McKenzie Flats, NM, USA	AmeriFlux	12	Desert Grassland	0.219
ShidlerOK	Shidler, OK, USA	AmeriFlux	4	Tall grass prairie	0.217
SantaRitaAZ	Santa Rita, AZ, USA	AmeriFlux	11	Semidesert grassland	0.204
TwitchellCA	Twitchell Island, CA, USA	AmeriFlux	5	Alfalfa	0.223
WalnutGulchAZ	Walnut Gulch, AZ, USA	AmeriFlux	15	Grassland	0.182
SmileyburgKS	Smileyburg, KS, USA	AmeriFlux	3	Tall grass prairie	0.210

II. Data Sets

A. Station Locations

Table I provides a list of measurement stations and their locations that are included in the albedo data base and the station identifier (*StationID*) assigned by NREL and used as part of the naming convention for the station's data files. The overall albedo is the average or mean yearly albedo. A yearly albedo is the sum of the GRIs during the year divided by the sum of the GHIs during the year. If measurements are for less than a year, the overall albedo represents the period of the measurements. The overall albedo includes the effects of snow if present.

B. Data Files

Data files are available at the original temporal resolution provided by the source of the data, and for an hourly temporal resolution derived from the higher resolution original data, as needed. A comma separated format (CSV) is used and data are assigned quality assessment (QA) flags to indicate if the data are reasonable. Headers define station locations and data element fields.

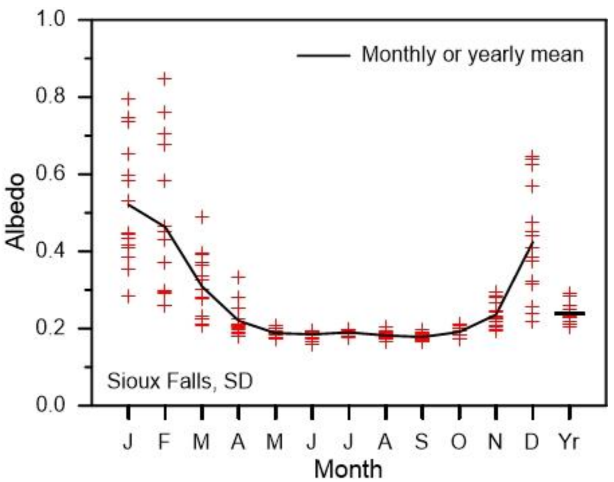

Fig. 1. Monthly and yearly albedo means for Sioux Falls, SD.

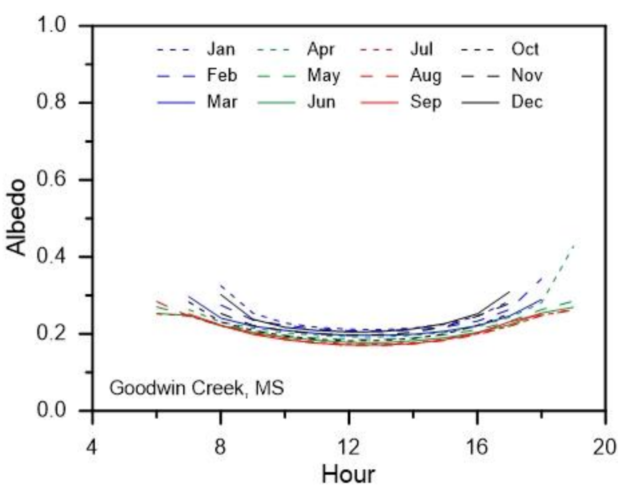

Fig. 2. Mean hourly albedos for Goodwin Creek, MS.

C. Summary Information

Albedo data are provided in tabular form by month and year and with the statistics for mean, median, minimum, maximum, and standard deviation. For visual representation, the user's guide includes plots of monthly and hourly albedos such as shown in Fig. 1 and Fig. 2. In Fig.1, the variability of albedo during the winter months is because the snowfall is variable.

D. Availability

The albedo data sets and a user's guide describing the data are available for download from NREL's DuraMAT website at https://datahub.duramat.org/project/about/albedo-study.

III. Albedo Characteristics

The albedo data sets also provide information about interannual variability, time-of-day and seasonal effects, enhancement benefits, and spectral effects.

A. Interannual Variability

The data for the SURFRAD network stations have measurement periods from 15 to 24 years. The standard deviation of the yearly albedo indicates how an albedo for an individual year might vary from the long-term mean. This information is shown in Table II.

The standard deviations range from 0.004 to 0.037, with the smallest values for locations not subject to snow (Desert Rock and Goodwin Creek). Based on two standard deviations, an albedo for an individual year has a 95% probability of being within 0.008 (4%) of the long-term mean for Desert Rock, but only within 0.074 (30%) for Fort Peck because of its year-to-year variability in snowfall.

TABLE II. SURFRAD Network Annual Albedo Statistics

Location	**Mean**	**Standard Deviation**
Bondville, IL, USA	0.247	0.015
Boulder, CO, USA	0.199	0.011
Desert Rock, NV, USA	0.211	0.004
Fort Peck, MT, USA	0.247	0.037
Goodwin Creek, MS, USA	0.200	0.006
Penn State Univ, PA, USA	0.252	0.019
Sioux Falls, SD, USA	0.238	0.025

B. Time-of-Day and Seasonal Effects

Fig. 2 illustrates both time-of-day and seasonal effects. Albedo increases for times when the sun elevation is less – early morning and late afternoon and during winter months. As discussed previously, this is because the distribution of the solar spectrum shifts to longer wavelengths for these times and the ground surface reflection is greater for the longer wavelengths, and because the incidence angle of the solar radiation is greater. These effects are both small and not easily separated.

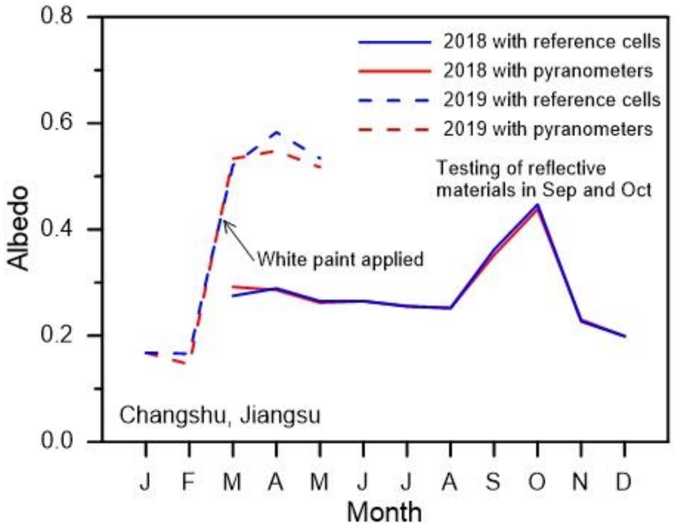

Fig. 3. Monthly albedos for Changshu, Jiangsu, China for a concrete surface with and without white paint at a Canadian Solar Inc. installation. Greater albedos in September and October are a result of testing proprietary reflective materials from 9/14/2018 to 10/12/2018.

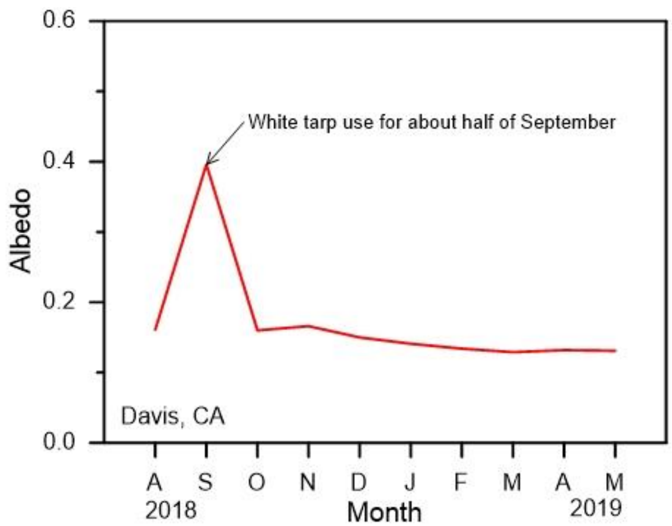

Fig. 4. Monthly albedos for Davis, CA for a light to medium gray gravel surface at a SunPower Corp. installation, except white tarp placed on the ground on 8/31/2018 and removed on 9/17/2018 which contributed to an increase in the albedo for the month of September. Albedo of white tarp determined to be 0.57 for the time it was in place.

C. Enhancement Benefits

An artificial surface can be used to enhance the albedo. Both Canadian Solar, Inc. and SunPower provided albedo data showing that the albedo can be increase to greater than 0.5 by using either white paint or a white tarp. Figs. 3 and 4 include this effect on the albedo when using these materials.

D. Spectral Effects

Some surfaces reflect solar radiation that results in a wavelength distribution of the reflected radiation that is more favorable for the operation of bifacial PV systems. One way to evaluate a spectral effect is to compare the albedo from albedometers using both thermopile pyranometers and crystalline silicon reference cells. In Fig. 3, this comparison is shown for before and after application of the white paint to the concrete surface. For the unpainted concrete, no spectral effect is apparent. Painted, the spectral effect was a positive 2.4%, an albedo of 0.546 when using the reference cells versus 0.533 when using the pyranometers.

Another way to evaluate albedo spectral effects uses modeled horizontal spectral irradiances and the spectral reflectance of the ground surface to determine the reflected spectral irradiance, which is then used with the PV spectral response for calculation of a spectral mismatch factor. Gostein et al. [4] applied this method for nine ground surfaces. A spectral benefit was shown for snow, white sand, dry soil, and green grass.

IV. Summary

For use by the PV and financial communities to better estimate the performance and to reduce the risk of bifacial PV systems, data sets of ground albedo and associated meteorological data were developed by using existing measurement network data and data contributed by the PV industry. The data sets include time-series data as well as summary information of tabular monthly and yearly data and plots of monthly and hourly albedo values. Complete information is presented in a user's guide and data are available for download from the DuraMAT website. This work will add more albedo data sets as they become available from contributions by the PV community.

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REFERENCES

[1] M. Iqbal. An Introduction to Solar Radiation, Academic Press, Inc., New York, 1983.

[2] J. Augustine, J. Deluisi, and C. Long, "SURFRAD - A national surface radiation budget network for atmospheric research," *Bulletin of the American Meteorological Society*, Vol. 81, pp. 2341-2357, 2000.

[3] https://ameriflux.lbl.gov/ , accessed May 20, 2020.

[4] M. Gostein, B. Marion, B. Stueve, "Spectral effects in albedo and rearside irradiance measurement for bifacial performance estimation," in IEEE 47th PVSC, 2020.