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Objective Method for Selecting Outdoor Reporting Conditions for Photovoltaic Performance

D.R. Myers and S. Kurtz
National Renewable Energy Laboratory

C. Whitaker and T. Townsend
Endecon Engineering; San Ramon, California

A. Maish
Sandia National Laboratories; Albuquerque, New Mexico

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Daryl R. Myers
Sarah Kurtz
National Renewable Energy Laboratory
1617 Cole Blvd, Golden CO 80401

Chuck Whitaker
Tim Townsend
Endecon Engineering
2500 Old Crow Canyon Road Suite 220
San Ramon CA 94583

Alex Maish
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-0752

ABSTRACT

Outdoor performance of photovoltaic modules and systems depends on prevailing conditions at the time of measurement. Outdoor test conditions must be relevant to device performance and readily attainable. Flat-plate, nonconcentrator PV device performance is reported with respect to fixed conditions referred to as Standard Reporting Conditions (SRC) of 1 kW/m² plane of array total irradiance, 25° C device temperature, and a reference spectral distribution at air mass 1.5 under certain atmospheric conditions. We report a method of analyzing historical meteorological and irradiance data to determine the range of outdoor environmental parameters and solar irradiance components that affect solar collector performance when the SRC 1 kW/m² total irradiance value occurs outdoors. We used data from the 30 year U.S. National Solar Radiation Data Base (NSRDB) , restricting irradiance conditions to within +/- 25 W/m² of 1 kW/m² on a solar tracking flat-plate collector. The distributions of environmental parameter values under these conditions are non-Gaussian and site dependent. Therefore the median, as opposed to the mean, of the observed distributions is chosen to represent appropriate outdoor reporting conditions. We found the average medians for the direct beam component (834 W/m²), ambient temperature (24.4° C), total column water vapor (1.4 cm), and air mass (1.43) are near commonly used SRC values. Average median wind speed (4.4 m/s) and broadband aerosol optical depth (0.08) were significantly different from commonly used values.

1. 0 INTRODUCTION

Consensus standards for reporting the performance of flat-plate photovoltaic (PV) devices are relatively well developed by interaction between PV industry and national PV research and development assets such as the Department of Energy (DOE) Photovoltaic Advanced Research and Development Program implemented at the National Renewable Energy Laboratory (NREL) National Center for Photovoltaics , Sandia National Laboratories, and the Photovoltaics for Utility Scale Applications (PVUSA) project.

Existing standards only address the performance of flat-plate, non-concentrator PV devices. Device performance is reported with respect to fixed conditions referred to as Standard Reporting Conditions(SRC). SRC (1) specify total irradiance (1 kW/m²) in the plane of the device or array (POA), device temperature (25° C), and a reference spectral distribution (2,3). The 1kW/m² irradiance condition was chosen as an arbitrary but convenient and generally achievable "peak" performance condition. We wished to investigate what prevailing direct normal irradiance (DNI) and outdoor reporting conditions might be for evaluating concentrating solar collectors *when the SRC reference total irradiance (1 kW/m²) occurs; not under the exactly defined SRC which require spectral and cell temperature information.*

2.0 FLAT-PLATE AND CONCENTRATOR TESTING

Performance testing of flat-plate PV devices may conveniently be conducted indoors, under simulated sunlight, at conditions very near SRC. American Society for Testing and Materials (ASTM) Standard Test Method E-948 (2) provides guidance to produce a report of electrical performance with respect to SRC under simulated sunlight. Because of the size and configuration of PV concentrator modules, indoor testing is prohibitively expensive and complicated.

There are currently no consensus standards for reporting PV concentrating collector performance, although draft standards are under development. Photovoltaics for Utility Scale Applications (PVUSA) implemented a set of conditions as a means of relating outdoor performance of PV systems for procurement purposes. PVUSA Test Conditions (PTC) have been widely adopted for PV system performance and rating. PTC are defined for flat plate (1000 W/m² POA) and concentrator (850 W/m² DNI) performance with common 20° C ambient temperature with 1 m/s wind speed (4). These conditions were selected based on PVUSA site-specific data for the appropriate value of DNI comparable to the 1 kW/m² POA irradiance for flat-plate collectors.

PTC ratings are determined using measured outdoor environmental and PV performance data in concert with a multiple linear regression model for PV power as a function of irradiance, ambient temperature, and wind speed (5).

PTC for PV concentrator collectors have been subject to controversy in comparisons with flat plate technologies. We wished to determine objectively the relationship between the flat-plate reference total global, concentrator DNI, and environmental parameters for fair comparisons of the technologies.

3.0 TECHNICAL APPROACH

As we were interested in studying conditions for concentrating collectors for comparison with flat plate collectors, sites were chosen based on (a) availability in the National Solar Radiation Data Base (NSRDB) and (b) clear skies. Data for the NSRDB (6) recorded on the Solar and Meteorological Surface Observation Network (SAMSON) CD-ROM disk developed jointly by NREL and the National Climatic Data Center (7).

The basis for selecting clear sky sites was the annual average clearness index, Kt. Kt is the ratio of measured global horizontal solar irradiance to the solar irradiance on a horizontal surface at the top of the atmosphere. All 239 sites (including Alaska) in the NSRDB were ranked according to Kt. The range of Kt values for all sites is from 0.681 to 0.345. Seventeen sites with the highest Kt ($0.608 \le Kt \le 0.681$) plus an additional 13 sites ($0.607 \le Kt \le 0.547$ to broaden the Kt range for the study) from the 70 highest Kt sites were selected. All sites (see Table 1) lay in the southwest continental United States.

We emphasize that the criteria for site selection for the deployment of any PV technology is _not_ *the purpose or result of this work; but is the subject of continuing research.*

The following approach could be applied to any region where sufficient solar and meteorological data are available. The analysis performed could be used in any other geographic region to establish prevailing conditions at any desired value of POA irradiance, or desired ranges of other variables.

We extracted 30 years of NSRDB hourly daylight global-horizontal, direct-normal, and diffuse-horizontal solar radiation, ambient temperature, wind speed, cloud cover, precipitable water, and broadband aerosol optical depth for the hours of 8 a.m. to 5 p.m. for each of the 30 sites. Each station data file contained 6.6 megabytes of data.

Global normal irradiance (GNI) for a tracking flat plate collector was modeled using the Perez Anisotropic Diffuse Model (8). An albedo of 0.2 was used to determine the ground reflected component of the modeled GNI. The model uses a parameterization of sky dome irradiance distributions as a function of air mass and ratios of global-horizontal to direct beam irradiances.

Two years of measured DNI, GNI, global-horizontal and diffuse-horizontal radiation from the NREL Solar Radiation Research Laboratory and one year of similar PVUSA data from the Davis, CA, test site near Sacramento, CA were used to evaluate model performance. The mean difference between the measured GNI and modeled GNI for measured GNI between 975 and 1025 W/m² was +5.5 Watt/m^2 (measured > modeled) with a standard deviation of 25 W/m^2. A histogram of the model error distribution is shown in Figure 1.

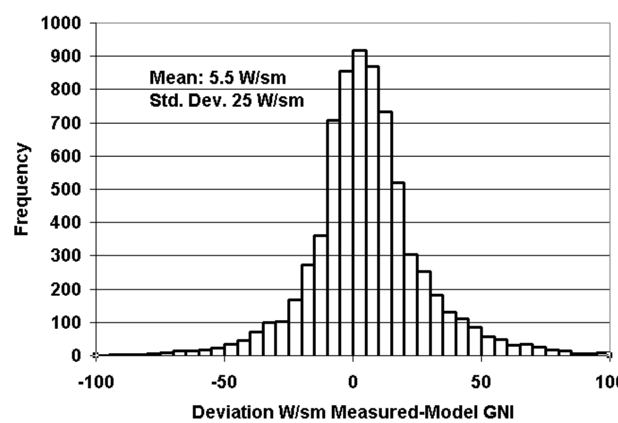

Fig. 1. Histogram of deviations between measured and modeled GNI for measured GNI between 975 and 1025 W/m²

When the GNI was between 975 and 1025 W/m^2, data were written to an output file for each station. Statistics were then computed on these filtered hourly data.

4.0 RESULTS

Often the mean and median values of the parameters for each site were not very different. However there was significant variation in the shape of the distributions from site to site. Therefore, median values were chosen as more representative of typical conditions. The median has the property that one half of the sample population is greater than, and one half of the population is smaller than the median. As shown in Table 1, the average median DNI value for all of our study sites was 834.4 W/m².

TABLE 1. MEDIANS FOR ENVIRONMENTAL CONDITIONS
975 W/M² ≤GNI ≤ 1025 W/M²

LOCATION	Hours, N	DNI W/m²	GNI W/m²	Temp. °C	Wind speed m/s	Total H2O cm	Turbidity	Air mass
DAGGETT	16115	860	1003	27.2	5.2	1.1	0.068	1.533
LAS VEGAS	12804	834	1002	26.7	3.6	0.9	0.070	1.633
TUCSON	14605	851	1001	28.9	3.6	1.3	0.064	1.382
ALBUQUERQUE	11484	836	1003	22.2	3.6	1.0	0.064	1.566
TONOPAH	12852	852	1001	20.0	4.1	0.8	0.055	1.552
PRESCOTT	11980	867	1001	21.8	4.1	1.0	0.050	1.415
PHOENIX	13908	814	1003	30.6	3.1	1.2	0.101	1.443
EL PASO	14476	821	1002	26.7	3.1	1.4	0.098	1.429
RENO	12582	849	1001	20.9	2.6	1.0	0.061	1.489
ALAMOSA	13734	875	1001	16.1	3.1	0.9	0.026	1.521
CEDAR CITY	11078	853	1001	20.6	4.1	0.9	0.049	1.394
FLAGSTAFF	10974	870	1000	16.7	4.1	0.8	0.049	1.449
ELY	10309	861	1002	18.2	4.1	0.8	0.041	1.637
WINNEMUCCA	11205	853	1001	22.2	4.1	1.0	0.057	1.502
GRAND JUNCTION	12475	845	1002	23.3	3.6	1.0	0.055	1.422
MIDLAND	10914	819	1001	27.8	6.2	1.7	0.080	1.369
ELKO	10516	863	1000	20.0	3.1	0.9	0.052	1.521
AMARILLO	11518	832	1001	24.4	6.7	1.6	0.071	1.412
TUCUMCARI	12266	841	998	24.1	5.2	1.3	0.062	1.411
LUBBOCK	11191	825	1001	25.8	6.2	1.8	0.076	1.387
SANTA MARIA	16733	818	1002	19.4	5.2	1.7	0.105	1.349
SAN ANGELO	11191	817	1000	28.3	5.2	2.1	0.083	1.375
ABLIENE	11190	821	1001	27.2	5.7	2.0	0.083	1.374
BAKERSFIELD	13925	813	1001	27.8	3.6	1.5	0.114	1.374
FRESNO	14548	806	1003	27.2	3.1	1.6	0.131	1.351
WICHITA FALLS	10973	821	999	27.4	6.2	2.0	0.085	1.361
SACRAMENTO	13662	814	1002	25.4	3.6	1.6	0.114	1.341
FORT WORTH	11188	806	1000	27.9	5.2	2.2	0.103	1.313
AUSTIN	9319	806	998	28.1	4.6	2.3	0.089	1.330
SAN ANTONIO	9984	789	999	28.9	4.6	2.4	0.091	1.327
AVERAGE (30 sites)		834.4	1001.0	24.4	4.4	1.4	0.075	1.432
St. Dev (30 sites)		22.76	1.34	4.0	1.1	0.5	0.025	0.090

This value is within 16 W/m², or 1.8 % of the PTC value of 850 W/m². Figure 2 is a histogram showing the (bimodal) distribution of median DNI values when GNI is within the 50 W/m² irradiance range around 1 kW/m².

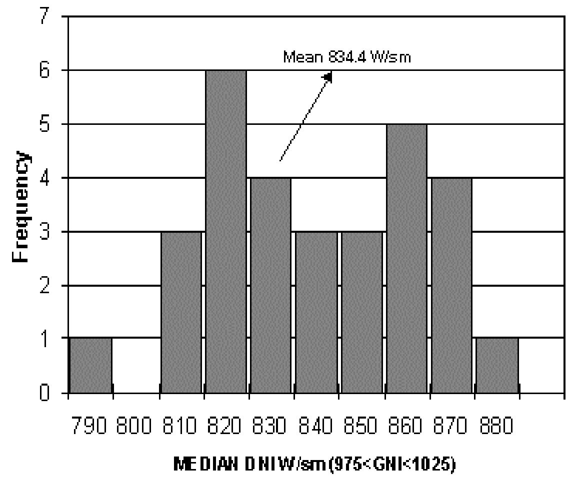

Fig 2. Histogram of median DNI for GNI Between 975 and 1025 W/m² for 30 southwest U.S. locations.

Typical measurement uncertainty is 2.5% in solar radiometers, or 25 W/m² at 1000 W/m². Therefore this difference is within typical measurement uncertainty limits. At these sites, an 850 W/m² value represents a fair concentrator test condition with respect to flat plate collector test conditions.

The average median ambient temperature and wind speed at the sites were 24.4°C and 4.4 m/s, respectively. It is likely that changing the temperature and wind speed specification to these values versus 20°C and 1 m/s for PTC might result in modest increases in reported PV peak power performance.

The distribution of hourly values of ambient temperature, broadband aerosol turbidity, total column water vapor (gray data points) and air mass environmental conditions over which the GNI flat-plate-rating irradiance occurs varies as a function of DNI from site to site, as shown in Figures 3 and 4.

Note the greater water vapor and broadband turbidity values for Fort Worth, and the more uniform distribution of parameters versus DNI for Daggett. The distributions of the parameters are not Gaussian, or normal. They are often skewed, bimodal , and vary significantly from site to site as shown in Figures 6 to 9.

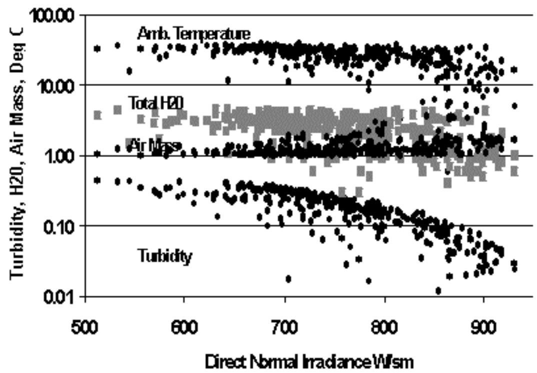

Fig. 3: Range of temperature, air mass, total water vapor (gray) , and turbidity versus DNI when GNI =1kW /m² +/- 25 W/m² at Fort Worth, TX 1961-1990.

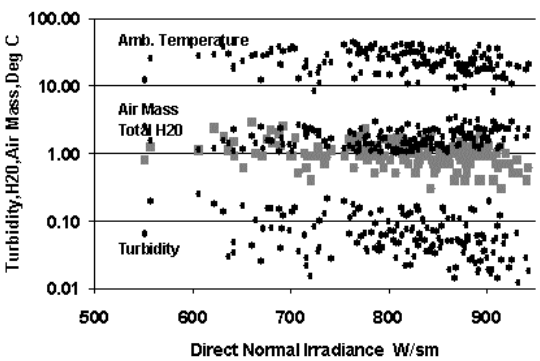

Fig. 4. Same as for Figure 3, except for Daggett, CA.

Figure 5 shows the difference in the distribution of DNI for GNI near 1 kW/m² at Daggett and Fort Worth, respectively.

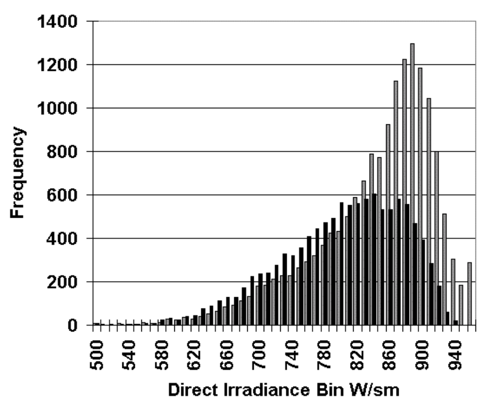

Fig. 5. Distribution of DNI (W/m²) for GNI near 1 kW/m² at Daggett, CA, (gray) and Fort Worth, TX (black).

Many sites demonstrated the Fort Worth "ramp" shape, and very clear sites demonstrated the sharply peaked shape of the Daggett distribution, with peaks between 810 and 870 W/m².

Differences in the temperature distributions at Dagett and Fort Worth are shown in Figure 6.

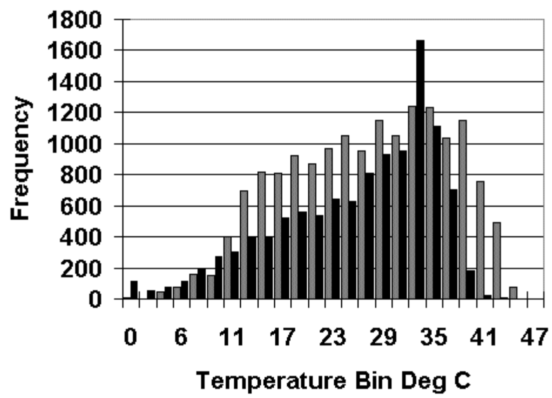

Fig. 6. Distribution of ambient Temperature at GNI near 1 kW/m² for Daggett, CA, (gray) and Fort Worth, TX (Black).

The broad temperature distribution for Daggett reflects the desert climate with high direct beam throughout the year. The more peaked Fort Worth distribution indicates high DNI and GNI occurring on hot, probably dry, occasions. Figure 7 shows the distribution of total column water vapor for the these two sites.

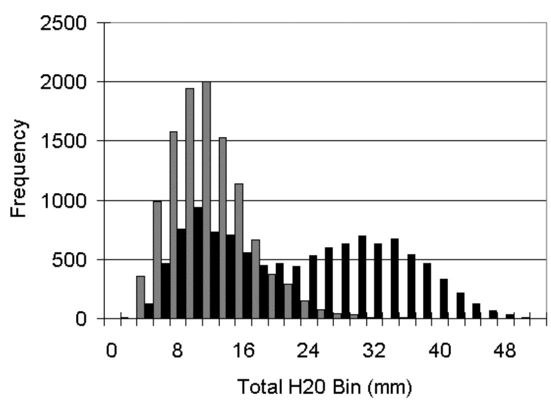

Fig. 7. Distribution of Total Column H2O for GNI near 1kW/m² at Daggett, CA, (gray) and Fort Worth, TX (black).

The Daggett total column water vapor distribution reflects the dry desert climate with a narrow range of low water vapor. The Fort Worth bimodal distribution of higher total water vapor probably represents seasonal fluctuations of water vapor under high GNI and DNI conditions.

Figure 8 shows the distribution of broadband aerosol optical depth for the two sites.

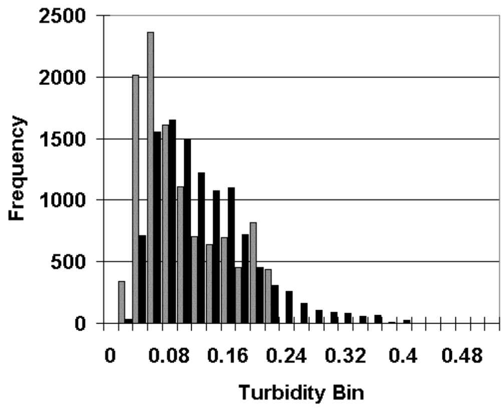

Fig. 8. Distribution of broadband aerosol optical depth (turbidity) for GNI near 1 kW/m^2 at Daggett, CA, (gray) and Fort Worth, TX (black).

The very low turbidity values under high GNI and DNI conditions at Daggett is typical of high western desert sites. The broader range of turbidity at Fort Worth reflects a lower-elevation, continental-plains location. For these high GNI and DNI conditions, the most common values of turbidity are in the range of 0.06 to 0.1, for all sites in the study.

As shown in Figure 9, the wind speed distributions under high GNI and DNI conditions for Daggett and Fort Worth are similar. The shapes of the wind speed distribution for many of the sites in Table 1 are similar, peaking between 4 and 7 m/s.

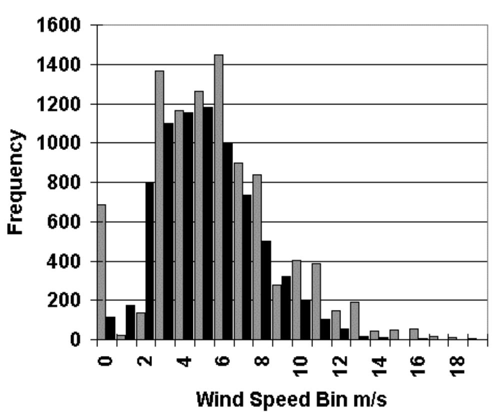

Fig. 9. Wind Speed distribution for Daggett, CA, (gray) and Fort Worth, TX, (black) for GNI near 1 kW/m^2

The question arises of whether the relationships between prevailing conditions when the SRC total irradiance occurs can be determined from irradiance and meteorological data under all conditions. This idea, and other issues such as new or revised consensus standards for PV performance reporting, spectral issues, and site selection for specific PV technologies are being studied in the light of these results (10).

5.0 SUMMARY

We used an objective statistical approach to examine a large data base of solar and meteorological data and establish prevailing outdoor conditions associated with the consensus standard plane-of- array global irradiance (1000 W/m^2) defined for PV device performance.

Global clearness index, Kt, was computed for the 239 sites in the U.S. NSRDB. For the 30 sites with Kt $(0.681 \le Kt \le 0.547)$, hourly GNI was modeled from 30 years of hourly DNI, global horizontal, and diffuse horizontal data. Hours when the modeled GNI was within +/-25 W/m^2 of 1000 W/m^2 were selected for analysis. The model uncertainty includes a mean bias error of 5.5 W/m^2 with a root-mean-square error of 25 W/m^2 for irradiances in this GNI range.

Histograms of meteorological parameter values for GNI near 1 kW/m^2 suggested that the distribution medians were most representative of typical conditions than means, due to the non-gaussian nature of the distributions.

The average of the DNI and environmental parameter medians at the southwestern U.S sites for flat-plate plane-of-array irradiance near 1000 W/m^2 are repeated in table 2.

TABLE 2. STATISTICS ON MEDIAN SITE ENVIRONMENTAL PARAMETERS FOR 30 SITES WITH Kt>0.584 AND 975 W/m^2<GNI<1025 W./m^2

Parameter	Mean of 30 Medians	Std. Dev.
Direct Normal	834.4 W/m^2	23 W/m^2
Ambient Temp	24.4 °C	4 °C
Wind Speed	4.4 m/s	1.1 m/s
Total H20 Vapor	14 mm	5 mm
Broadband AOD	0.08	0.03
Air Mass	1.43	0.09

For the 30 sites studied, the mean DNI median value is within 16 W/m² of the value developed for PVUSA test conditions, within typical solar radiometer measurement uncertainty of 2.5% of full scale = 1000 W/m². For these sites the 850 W/m² value adopted for the PVUSA tests for concentrating technologies appears to be representative of DNI at GNI levels near the SRC total irradiance. In addition, the average median air mass, and total water vapor are near values (1.5 and 1.4 cm, respectively) used to define SRC spectrum.

Consensus SRC are tied to a reference spectrum that reflects a U.S. Standard Atmosphere with a rural aerosol optical depth (AOD) of 0.27 (3). We found a more typical value for AOD is about 0.08-0.10 in our study area. Even though true monochromatic AOD is not exactly equal to the "broadband" AOD reported in the NSRDB, the broadband AOD is equivalent to a monochromatic AOD at a wavelength of approximately 700 nm (9). This difference in AOD between prevailing conditions and the consensus standard spectrum AOD has a very large effect on the spectral distribution under the two conditions.

The ramifications of these differences and their impact regarding design and validation of consensus standards for PV performance testing and rating is a subject of continuing research and discussion in the community.

6.0 ACKNOWLEDGMENTS

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