Comparison of Predicted PV System Performance with SURFRAD versus TMY

Mark A. Mikofski and Rounak Kharait
DNV, Oakland, CA, 94612, USA

***Abstract*—Solar resource is important for predicting PV system performance. Historical Typical Meteorological Years (TMY) from 1960-1990 (TMY2) and 1990-2010 (TMY3) are commonly used in the United States, but recently there have been concerns by stakeholders whether these datasets may lead to overpredictions. Therefore we simulated performance of a fictional PV system with over 20-years of accurate ground based surface radiation (SURFRAD) measurements at 7 locations and compared the median year performance with simulations using TMY data. We found that TMY overpredicted the median SURFRAD performance at 5 of the 7 sites, the NREL Physical Solar Model V3 (PSM3) performance predictions were greater than 90% of SURFRAD years at 5 of the 7 sites, and TMY3 predictions were closest on average to the median. Both TMY2 and TMY3 were within their uncertainty range.**

***Index Terms*—SURFRAD, TMY, irradiance, PV, performance, prediction**

I. Introduction

Investors require accurate predictions of PV system performance to quantify and manage their risks. However, there is growing concern about under-performing PV systems [1]. Predictions commonly use TMY datasets developed from historical data. There are many sources of TMY datasets, but we focused on three publicly available TMY datasets from the National Renewable Energy Laboratory (NREL), and compared them with accurate, ground-based, high-frequency SURFRAD data at 7 sites from 1995 until present day [2] by simulating a fictional PV system. Our goal was to determine if the predictions with TMY data would yield the same median performance we simulated with the SURFRAD data, but we discovered the TMY overpredicted performance for all sites except Penn State, PA, and Goodwin Creek, MS. The predictions with PSM3 were greater than 90% of SURFRAD years at all sites except Boulder, CO and Fort Peck, MT. The predictions with TMY2 were greater than 30-90% of years at 6 sites excluding Desert Rock, NV which doesn't have a nearby TMY2 site. On average, predictions with TMY3 were closest to the SURFRAD median with a standard deviation of 2.8% of the annual DC capacity factor. In the following sections we will describe the methods, present our results, and discuss our conclusions.

II. Methods

A. Locations

There are 7 SURFRAD stations [2] across the United States with 1 to 3 minute resolution. Fig. 1 shows the SURFRAD site locations. We selected TMY2 [3] and TMY3 [4] sites within 120[km] from the SURFRAD site that did not have any significant monthly irradiance, temperature, or wind speed deviations from the other nearby datasets. The generic uncertainty for both TMY2 and TMY3 is 5-8% at 95% confidence. For each SURFRAD site the PSM3 was queried for the nearest location using pvlib python [5]. Table I shows the station names, global coordinates, and metadata about each site. The error from the SURFRAD median in the last column will be discussed later in the results, Section III.

B. Annual Energy Prediction

We used pvlib python [5] to calculate the solar position for each site and the rotations for a fictitious single-axis tracker system. We used the SURFRAD measured global horizontal irradiance (GHI) and decomposed it into direct normal irradiance (DNI) and diffuse horizontal irradiance [6], then transposed it to the plane of the array (POA) accounting for diffuse components, ground reflection, and incidence angle modifiers [7]. We assume isotropic sky diffuse and an albedo of 0.25 for ground diffuse. To get the effective irradiance, we combined the POA components applying the ASHRAE incidence angle modifiers with $b_0 = 0.05$ to the direct irradiance and neglected spectral mismatch. Because SURFRAD doesn't include ambient temperature, we used RdTools [8] to get clear sky temperatures, and then scaled it to the daily ratio of SURFRAD GHI to calculated clear sky GHI [9] using (1). We used the PVsyst model to estimate module cell temperatures with default coefficients, $U_c = 29, U_v = 0$, the adjusted air temperature, and zero wind speed [10]. Finally, we predicted the DC power for a representative 300[W] mono-crystalline silicon module (Canadian Solar CS6X-300M) with the CEC 6-parameter model [11]. Then we resampled the data at hourly frequency and summed each day (2) and year (4). All years that had less than 350 days were removed and the annual energy was scaled to a full year accounting for leap years. We normalized by the module nameplate of 300[W] to get daily and annual DC capacity factors (CP) using (3) and (5). Then we repeated the simulations with PSM3 [12], TMY2 [3], and TMY3 [4], but using the measured ambient temperature provided in the data set. The full model is available online (https://github.com/mikofski/PVRW2021).

$$\begin{aligned} T_{adj} &= T_{clearsky} + \left(\frac{GHI}{GHI_{clearsky}} - 1\right)\Delta T \\ \Delta T &= T_{max,daily} - T_{min,daily} \end{aligned} \tag{1}$$

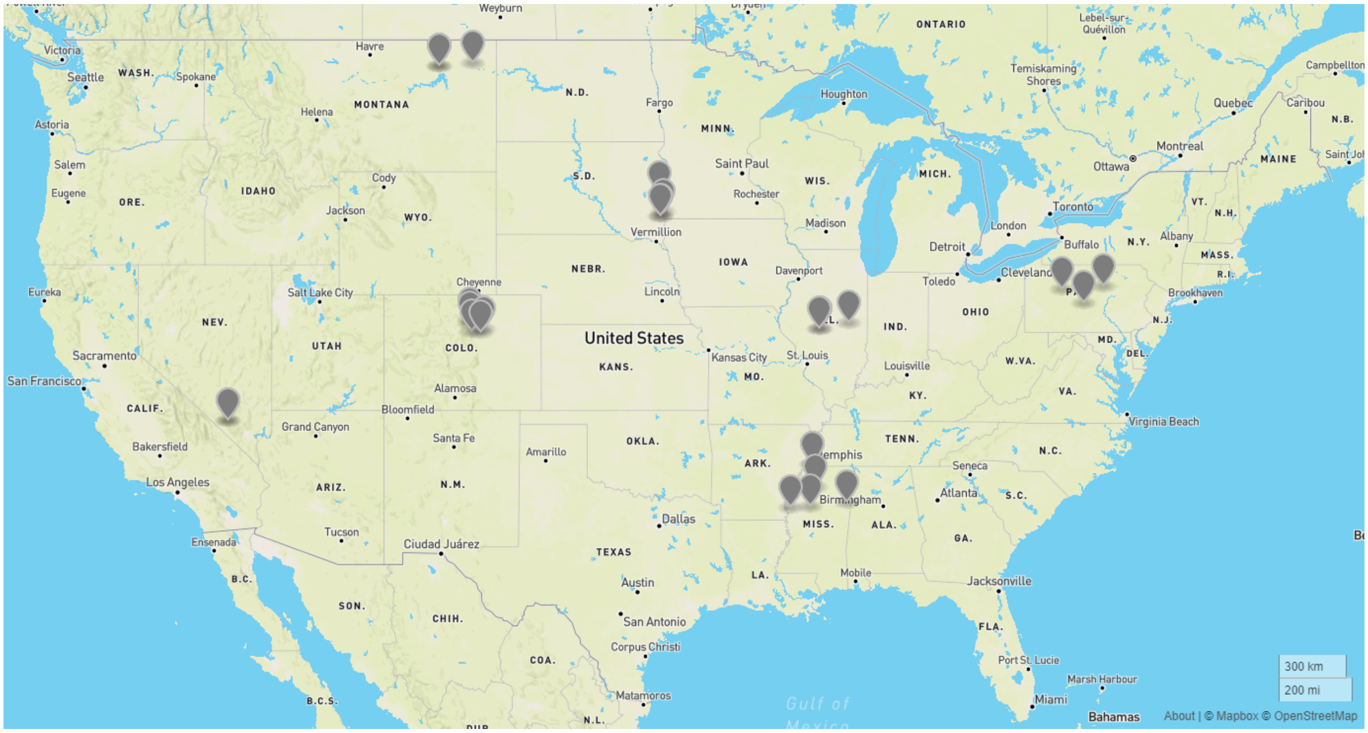

Fig. 1. Map of SURFRAD sites and selected nearby TMY2 and TMY3 sites for comparison.

TABLE I
SUMMARY OF SURFRAD, NSRDB, AND TMY LOCATIONS

Station	***Latitude***	***Longitude***	***Elevation***	***TMY***	***ID***	***Error***
Bondville, IL	40.05	-88.37	213	SURFRAD	bon	
NSRDB	40.05	-88.38	213	PSM3	887015	8.9%
SPRINGFIELD, IL	39.83333333	-89.66666667	187	TMY2	93822	4.9%
SPRINGFIELD CAPITAL AP	39.85	-89.683	179	TMY3	724390	2.9%
Boulder, CO	40.13	-105.24	1689	SURFRAD	tbl	
NSRDB	40.13	-105.22	1616	PSM3	150658	1.3%
BOULDER, CO	40.01666667	-105.25	1634	TMY2	94018	1.9%
DENVER INTL AP	39.833	-104.65	1650	TMY3	725650	0.6%
AURORA BUCKLEY FIELD ANGB	39.717	-104.75	1726	TMY3	724695	0.8%
DENVER/CENTENNIAL [GOLDEN - NREL]	39.742	-105.179	1829	TMY3	724666	-1.8%
Desert Rock, NV	36.62	-116.02	1007	SURFRAD	dra	
NSRDB	36.61	-116.02	991	PSM3	109824	4.0%
MERCURY DESERT ROCK AP [SURFRAD]	36.63	-116.02	935	TMY3	723870	1.0%
Fort Peck, MT	48.31	-105.1	634	SURFRAD	fpk	
NSRDB	48.33	-105.1	629	PSM3	250489	3.0%
GLASGOW, MT	48.21666667	-106.6166667	700	TMY2	94008	1.6%
GLASGOW INTL ARPT	48.217	-106.617	699	TMY3	727680	2.3%
Goodwin Creek, MS	34.25	-89.87	98	SURFRAD	gwn	
NSRDB	34.25	-89.86	95	PSM3	852772	13.3%
MEMPHIS, TN	35.05	-89.98333333	87	TMY2	13893	6.5%
GREENWOOD LEFLORE ARPT	33.5	-90.083	47	TMY3	722359	3.9%
GREENVILLE MUNICIPAL	33.483	-90.983	42	TMY3	722356	3.4%
MEMPHIS INTERNATIONAL AP	35.067	-89.983	81	TMY3	723340	2.9%
COLUMBUS AFB	33.65	-88.45	68	TMY3	723306	-1.6%
Penn State, PA	40.72	-77.93	376	SURFRAD	psu	
NSRDB	40.73	-77.94	378	PSM3	1116869	8.8%
WILLIAMSPORT, PA	41.26666667	-77.05	243	TMY2	14778	-2.5%
DUBOIS FAA AP	41.183	-78.9	553	TMY3	725125	-5.5%
Sioux Falls, SD	43.73	-96.62	473	SURFRAD	sxf	
NSRDB	43.73	-96.62	479	PSM3	706377	6.1%
SIOUX FALLS, SD	43.56666667	-96.73333333	435	TMY2	14944	1.8%
SIOUX FALLS FOSS FIELD	43.583	-96.75	433	TMY3	726510	0.4%
BROOKINGS (AWOS)	44.3	-96.817	502	TMY3	726515	-3.5%

$$E_{\text{daily}} = \sum_{\text{time=1AM}}^{\text{12AM}} E_{\text{hourly}} \tag{2}$$

$$CP_{\text{daily}} = \frac{E_{\text{daily}}}{24[\text{h}]\text{Nameplate}[\text{W}]} \tag{3}$$

$$E_{\text{annual}} = \sum_{\text{day=1}}^{365} E_{\text{daily}} \tag{4}$$

$$CP_{\text{annual}} = \frac{E_{\text{annual}}}{8760[\text{h}]\text{Nameplate}[\text{W}]} \tag{5}$$

III. Results

A. Analysis

We plotted histograms of the annual predictions using SURFRAD data for each of the 7 sites in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7, and Fig. 8. The top plot shows the daily capacity factors (3) and annual capacity factors overlaid in red (5), while the bottom plot shows the histogram of annual energy per module (4) with the median (P50) and 90% chance of exceedance (P90) marked with dashed blue lines. Then we overlaid the predicted PSM3, TMY2, and TMY3 predictions and annotated the plot with their quantiles.

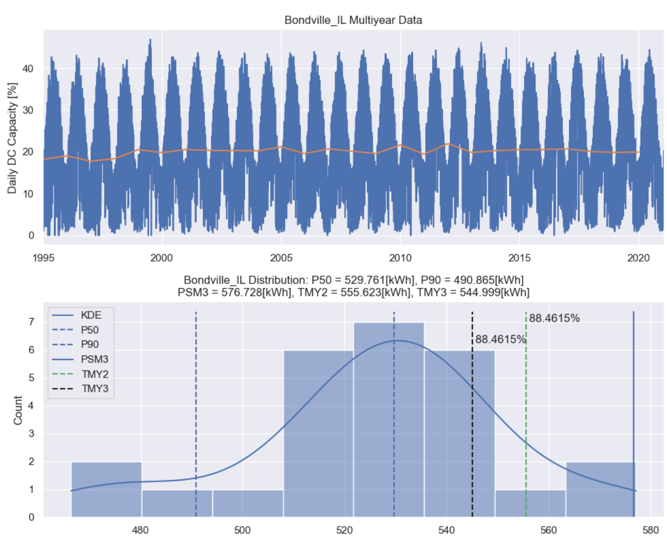

Fig. 2. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Bondville, IL, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

Table II shows the relative differences between the TMY annual prediction and the SURFRAD median (6) so that positive errors mean the TMY overpredicted. Table III summarizes the results as annual capacity factors (5), and Table IV summarizes the results as quantiles. Where more than one TMY3 was close to the SURFRAD station, the closest to the median is shown in the tables. The relative differences for all sites are shown in the last column of Table I.

$$Error = \frac{CP_{TMY}}{CP_{SURFRAD,P50}} - 1 \tag{6}$$

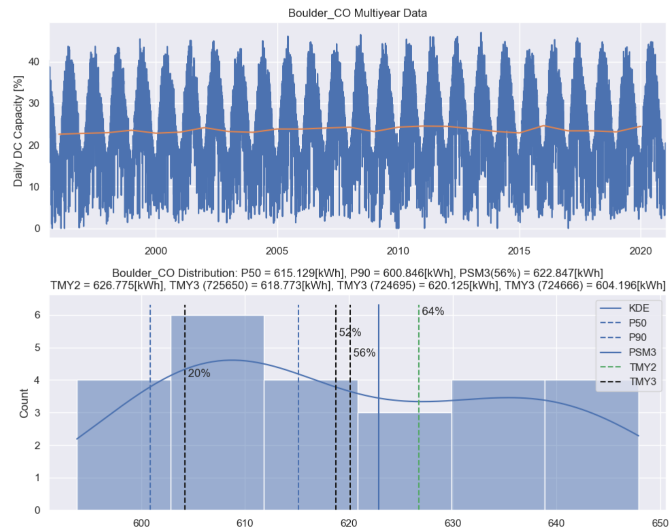

Fig. 3. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Boulder, CO, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

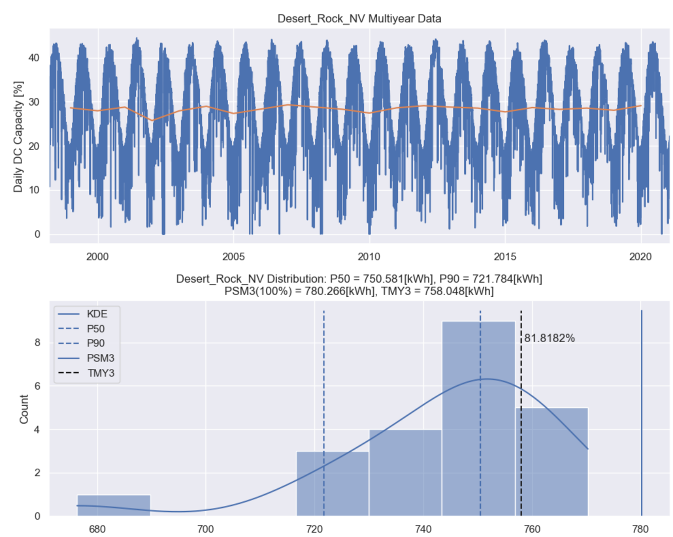

Fig. 4. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Desert Rock, NV, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

TABLE II
Summary of Differences Between SURFRAD median and TMY Annual Predictions

Station	***PSM3***	***TMY2***	***TMY3***
bon	8.9%	4.9%	2.9%
tbl	1.3%	1.9%	0.6%
dra	4.0%		1.0%
fpk	3.0%	1.6%	2.3%
gwn	13.3%	6.5%	-1.6%
psu	8.8%	-2.5%	-5.5%
sxf	6.1%	1.8%	0.4%
AVG	6.5%	2.4%	0.0%
STD	4.2%	3.1%	2.8%

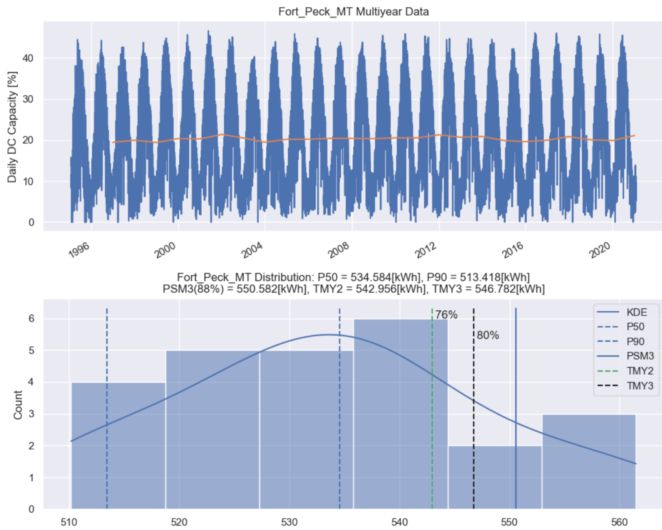

Fig. 5. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Fort Peck, MT, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

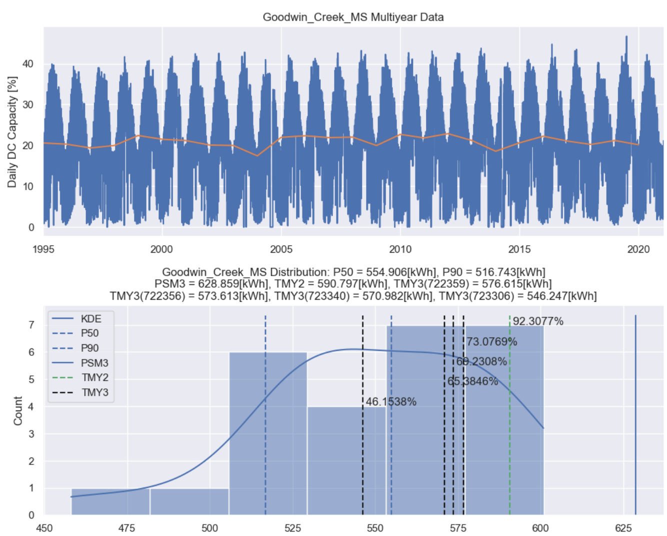

Fig. 6. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Goodwin Creek, MS, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

TABLE III
SUMMARY OF PREDICTED SURFRAD ANNUAL CAPACITY FACTORS COMPARED WITH TMY

SURFRAD Station	*P50*	*P90*	*PSM3*	*TMY2*	*TMY3*
Bondville, IL	20.2%	18.7%	21.9%	21.1%	20.7%
Boulder, CO	23.4%	22.9%	23.7%	23.8%	23.5%
Desert Rock,NV	28.6%	27.5%	29.7%		28.8%
Fort Peck, MT	20.3%	19.5%	21.0%	20.7%	20.8%
Goodwin Creek, MS	21.1%	19.7%	23.9%	22.5%	20.8%
Penn State, PA	18.6%	17.2%	20.2%	18.1%	17.5%
Sioux Falls, SD	20.7%	19.6%	22.0%	21.1%	20.8%

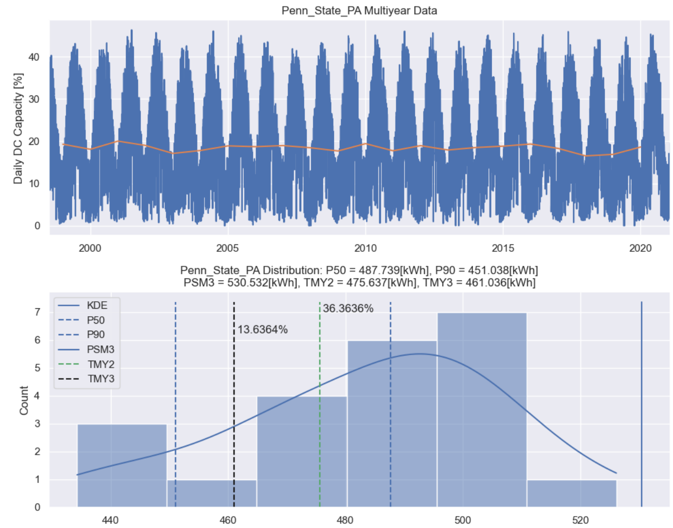

Fig. 7. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Penn State, PA, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

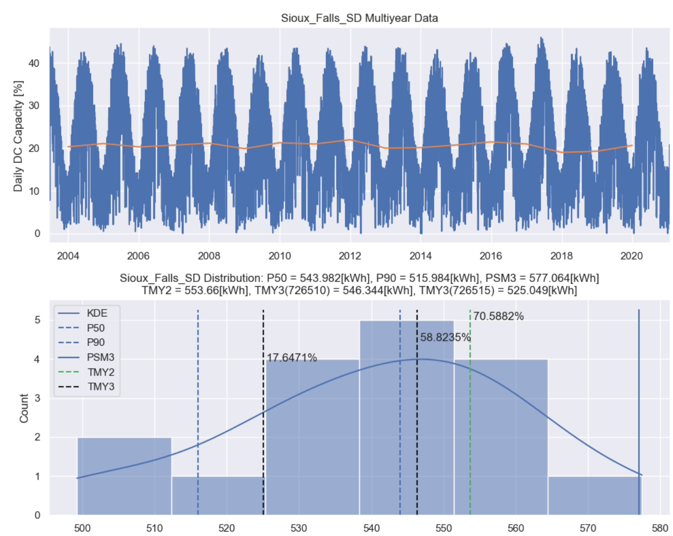

Fig. 8. Daily (blue) and annual (red) capacity factor relative to DC nameplate for Sioux Falls, SD, SURFRAD site (top) and distribution of annual DC energy per module (bottom).

TABLE IV
SUMMARY OF TMY QUANTILES OF SURFRAD YEARS

SURFRAD Station	*PSM3*	*WBAN*	*TMY2*	*USAF*	*TMY3*
Bondville, IL	96.2%	93822	88.5%	724390	88.5%
Boulder, CO	56.0%	94018	64.0%	725650	52.0%
Desert Rock, NV	100%			723870	81.8%
Fort Peck, MT	88.0%	94008	76.0%	727680	80.0%
Goodwin Creek, MS	100%	13893	92.3%	723306	46.2%
Penn State, PA	100%	14778	36.4%	725125	13.6%
Sioux Falls, SD	94.1%	14944	70.6%	726510	58.8%

B. Discussion

It's difficult to spot any trends in the 20 or more years of data at each of the SURFRAD sites, compared to trends seen in other studies [13]. Although there are some biases detected between the SURFRAD data and the oldest data set, TMY2 1960-1990 [3], the average difference from Table II, 2.4%, is on the same order as the standard deviation between the sites, 3.1%, and is therefore inconclusive. The newer data set, TMY3 1990-2010 [4], seems closer to the SURFRAD data, 0% average difference, but the standard deviation between sites, 2.8%, is similar to the spread for the TMY2, so they appear to overlap and are not clearly distinguishable. The newest data surprisingly is an outlier with an average difference twice as big as for TMY2, 6.5%, and a spread on the same order as TMY2 and TMY3, 4.2%, so there's a clear distinction between it and the other datasets. More investigation is necessary to understand the difference.

The distribution of years differs between SURFRAD sites, perhaps due to climate differences. Bondville, IL, Fig. 2 and Sioux Falls, SD, Fig. 8 seem to be the most normal and symmetrical with ranges of about 10%, but not all of the histograms show a normal distribution, some are flatter, many skewed, and some possibly multimodal. The range varies from site to site, between 5-10%. Fort Peck, MT, Fig. 5 has the closest range between 510-560[kWh/yr] per module. Desert Rock, NV, Fig. 4 also has a tight range and the highest output of all the sites, but also has a long downside tail. The year 2002 is an outlier at this site and is about 50[kWh/yr] per module lower than the other years. Goodwin Creek, MS, Fig 6 also has a long downside tail and apparently no upside or a double peak. The years 2004 and 2014 are outliers in this data set deviating by nearly 20-25% from previous and later years.

These SURFRAD sites do not cover all of the climates and regions in the US consistently. Most of the sites are in the interior, and there is a high concentration in the midwest. The average annual DC capacity factor is about 20% with Desert Rock, NV, the exception at 28%. There are no SURFRAD sites in the northwest, along the Pacific Coast, along the Gulf of Mexico, the Atlantic coast, or in the southeast, and there is only one site in the southwest, where there may be a high concentration of PV systems. For example Arizona or New Mexico. Therefore, the results of this study are limited and should not be extrapolated or applied uniformly to the entire United States.

IV. Conclusions

We studied the question of whether TMY datasets are representative of the median predicted PV performance by comparing PV system simulations using TMY data with simulations using over 20 years of high-frequency, accurate, ground based SURFRAD measurements at 7 sites across the United States. We found that the TMY datasets all overpredicted the median SURFRAD annual performance at 5 of 7 sites. The PSM3 predictions were greater than the median for all sites, and greater than 90% of years in 5 of 7 sites. TMY2 predictions were greater than 30-90% of years at 6 sites except Desert Rock, NV which had no nearby TMY2 station. On average TMY3 predictions were closest to the SURFRAD median. Differences between the SURFRAD median and both TMY2 and TMY3 were within their uncertainties. Due to the lack of number of SURFRAD stations it is difficult to conclude whether there is a *generic* high bias for TMY data. Although there is trend of generic high bias for PSM3 data, it is important to consider all available datasets and scrutinize them to determine the viability of long-term representative datasets. The distribution of differences from the SURFRAD median for both TMY2 and TMY3 stations were indiscernible; hence careful analysis is required to determine their utility in determining a long-term data set.

References

[1] R. Matsui, J. Moore, C. Nunalee, L. Garcia da Fonseca, N. Vadhavkar, J. Crimmins, S. Dise, J. Ahmad, I. Gregory, J. Fort, and J. Corbitt, "Solar Risk Assessment: 2020 Quantitative Insights from the Industry Experts," kWh Analytics, Tech. Rep., 2020. [Online]. Available: https://www.kwhanalytics.com/solar-risk-assessment

[2] J. A. Augustine, J. J. DeLuisi, and C. N. Long, "SURFRAD - A national surface radiation budget network for atmospheric research," *Bulletin of the American Meteorological Society*, vol. 81, no. 10, pp. 2341–2357, 2000.

[3] W. Marion and K. Urban, "User's Manual for TMY2s (Typical Meteorological Years) - Derived from the 1961-1990 National Solar Radiation Data Base," National Renewable Energy Laboratory (NREL), Golden, CO (United States), Tech. Rep. D, jun 1995. [Online]. Available: https://www.osti.gov/biblio/87130

[4] S. Wilcox, "National Solar Radiation Database 1991–2010 Update: User's Manual ," *Nrel/Tp-5500-54824*, no. August, 2012. [Online]. Available: http://www.nrel.gov/docs/fy12osti/54824.pdf

[5] W. F. Holmgren, C. W. Hansen, and M. A. Mikofski, "pvlib python: a python package for modeling solar energy systems," *Journal of Open Source Software*, vol. 3, no. 29, p. 884, sep 2018. [Online]. Available: http://joss.theoj.org/papers/10.21105/joss.00884

[6] D. Erbs, S. Klein, and J. Duffie, "Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation," *Solar Energy*, vol. 28, no. 4, pp. 293–302, 1982. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0038092X82903024

[7] J. Hay and J. Davies, "Calculation of the solar radiation incident on an inclined surface," *Proceedings of the First Canadian Solar Radiation Data Workshop*, pp. 59–72, 01 1980.

[8] D. C. Jordan, C. Deline, S. R. Kurtz, G. M. Kimball, and M. Anderson, "Robust PV Degradation Methodology and Application," *IEEE Journal of Photovoltaics*, vol. 8, no. 2, pp. 525–531, 2018.

[9] P. Ineichen and R. Perez, "A new airmass independent formulation for the Linke turbidity coefficient," *Solar Energy*, vol. 73, no. 3, pp. 151–157, sep 2002. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0038092X02000452

[10] D. Faiman, "Assessing the outdoor operating temperature of photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 4, pp. 307–315, 2008. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.813

[11] A. P. Dobos, "An Improved Coefficient Calculator for the California Energy Commission 6 Parameter Photovoltaic Module Model," *Journal of Solar Energy Engineering*, vol. 134, no. 2, p. 021011, 2012. [Online]. Available: http://dx.doi.org/10.1115/1.4005759

[12] A. Habte, M. Sengupta, A. Lopez, A. Habte, M. Sengupta, and A. Lopez, "Evaluation of the National Solar Radiation Database (NSRDB Version 2): 1998 – 2015 Evaluation of the National Solar Radiation Database (NSRDB Version 2): 1998 – 2015," *NREL/TP-5D00-67722*, no. April, pp. 1998–2015, 2017.

[13] B. Müller, M. Wild, A. Driesse, and K. Behrens, "Rethinking solar resource assessments in the context of global dimming and brightening," *Solar Energy*, vol. 99, pp. 272–282, jan 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0038092X13004933