Estimating Surface Solar Irradiance Using Meteosat-8 Satellite for India and Surrounding Regions (2017–2019)

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National Renewable Energy Laboratory

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Errata

This report, originally published in February 2021, has been revised in June 2021 to update and correct the author list.

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List of Acronyms

BSRN	Baseline Surface Radiation Network
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
FARMS	Fast All-Sky Radiation Model for Solar Applications
GHI	global horizontal irradiance
MAE	mean absolute error
MBE	mean bias error
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
NREL	National Renewable Energy Laboratory
PSM	Physical Solar Model
RMSE	root mean square error

Executive Summary

Using the Physical Solar Model, Version 3 (PSM V3), the National Renewable Energy Laboratory—in collaboration with the University of Wisconsin and the National Oceanic and Atmospheric Administration—produced modeled surface solar irradiance based on Meteosat-8 satellite cloud information. PSM V3 implements a physics-based radiative transfer approach to model surface solar irradiance using cloud properties processed from raw satellite data and ancillary data, such as aerosol optical depth and precipitable water vapor, from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Further, the modeled surface solar irradiance data were validated using data from 10 high-quality ground measurement stations from the Baseline Surface Radiation Network. The modeled data showed good correlation with the ground measurement data, and the overall uncertainty is less than 35% for all validation locations. Because of the satellite viewing geometry, the Indian and European locations demonstrated higher uncertainties than the African locations, where the Meteosat-8 satellite has a more nadir viewing geometry. This report also provides instruction on how to access the data.

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Introduction

As solar energy systems continue to become more prevalent, utility planners and grid system operators will need to understand how high penetrations of solar energy systems, which depend on the variable solar resource, will impact the electric grid. To do this appropriately, utility planners will need to model the long-term performance and the short-term variability of solar technologies and synchronize the solar generation with the load and other variable generation sources, such as wind. This will require high-resolution solar radiation data for long periods of time and a clear understanding of the spatial and temporal correlation of the data to determine the true impact of solar variability on the grid (Sengupta et al. 2017). A bottleneck to the process is the availability of high-quality direct normal irradiance (DNI) and global horizontal irradiance (GHI) for long periods of time. Although surface measurements have the highest quality measurements, it is not practical to obtain such measurements for solar resource assessment on a regional scale. In addition, although a site of interest might be instrumented now, it would take years to produce a time series that is long enough to provide dependable and sufficient data for the required analysis. On the other hand, methods to retrieve DNI and GHI from satellite measurements have been developed and used to overcome both the problem of spatial coverage and the availability of a long time series.

With the availability of faster computers, it is now possible to apply physics-based methods—such as the National Renewable Energy Laboratory’s (NREL’s) Physical Solar Model (PSM)—to data sets obtained from the Indian Ocean Data Coverage provided by the Meteosat series of satellites. Physical methods are based explicitly on the physics of the remote sensing problem, so it is possible to create a map of cloud properties as an initial step in the analysis. Ultimately, this enables radiative transfer calculations using those properties, and therefore both DNI and GHI can be computed directly.

NREL—in collaboration with the University of Wisconsin and the National Oceanic and Atmospheric Administration—developed the PSM, which uses cloud properties from satellite retrievals and then uses those properties to calculate surface radiation (Sengupta et al. 2018; Sengupta et al. 2017).

1 Method

The PSM model (Figure 1) is used to produce solar resource data for India and the surrounding regions. The model has the capabilities to use data from new generation satellites, such as the weather satellite Meteosat-8, also known as Meteosat Second Generation 1, which currently provides the Indian Ocean Data Coverage to produce solar resource at a 15-minute temporal and 4-km by 4-km spatial resolution (data can be accessed at <https://nsrdb.nrel.gov>). The data set was validated using high-quality, high-resolution ground measurement stations that were selected from the Baseline Surface Radiation Network (BSRN). The data from these stations are collected by well-maintained thermopile pyranometers (Driemel et al. 2018). Ten BSRN stations were selected for validation.

Figure 1. Flowchart of the PSM process¹

Data from 10 observation stations (Table 1) were used as the reference data in this study. These stations are distributed across the Meteosat Indian Ocean Data Coverage domain (Figure 2).

The satellite data that are used as input to the PSM characterize the cloud cover information into one of approximately 12 different classes. In this validation, these are then further categorized as clear, cloudy, or missing. Finally, a super category of all-sky is defined that includes each time step.

¹ See Xie, Sengupta, and Dudhia (2016) for the Fast All-Sky Radiation Model for Solar Applications (FARMS).

Table 1. Ground Observation Descriptions

Station Full Name	Abbreviation	Location	Latitude	Longitude	Elevation (m)
Carpentras	CAR	France	44.083	5.059	100
Cener	CNR	Spain, Navarra	42.816	-1.601	471
De Aar	DAA	South Africa	-30.6667	23.993	1287
Gandhinagar	GAN	India	23.1101	72.6276	65
Gobabeb	GOB	Namibia, Namib Desert	-23.5614	15.042	407
Gurgaon	GUR	India	28.4249	77.156	259
Howrah	HOW	India	22.5535	88.3064	51
Lindenberg	LIN	Germany	52.21	14.122	125
Sonnblick	SON	Austria	47.054	12.9577	3108.9
Tamanrasset	TAM	Algeria	22.7903	5.5292	1385

Figure 2. Location of the stations used in this study

To conduct a valid and reasonable data comparison, data quality assessment and data-filtering techniques were implemented for both the reference ground measurements and the satellite-derived data set (2017–2019) from the PSM. The following criteria were used to produce a quality-controlled data set for this validation study:

- Solar zenith angles must be less than 80° .
- GHI and DNI irradiance must be greater than 50 W/m^2 .
- Data records with missing values from the surface measurements were excluded from both the surface measurements and the satellite-derived data set.
- Cloud types from the satellite data were used to determine sky conditions.
- Ending time stamp averaging of the ground measurement (15 minutes) was used.

Statistical measures were used to investigate the performance of the satellite-derived data set relative to ground-based measurements. These included mean bias error (MBE), mean absolute error (MAE), and root mean square error (RMSE).

MBE in percentage (%) was calculated using the following equation:

$$\text{MBE (\%)} = \frac{\frac{1}{n} \sum_{i=1}^n (x_i - x_{\text{true}})}{\frac{1}{n} \sum_{i=1}^n (x_{\text{true}})} \times 100$$

where x_i represents values from the satellite-derived data set (2017–2019); and x_{true} represents the concurrent ground-measured data for both GHI and DNI, which were evaluated separately. MAE was calculated using a method similar to that used for the MBE calculations but by using absolute values of the difference.

Similarly, the RMSE values were computed using ground measurements (x_{true}):

$$\text{RMSE (\%)} = \frac{\frac{1}{n} \sum_{i=1}^n (x_i - x_{\text{true}})^2}{\frac{1}{n} \sum_{i=1}^n (x_{\text{true}})^2} \times 100$$

These statistics provide insight into the performance of the modeled data set relative to the ground-based measurements (Šuri and Cebecauer 2014; Sengupta et al. 2017). For instance, RMSE and MAE are useful in determining the error distribution (Chai and Draxler 2014). A large difference between the RMSE and MAE indicates a greater variance in the individual errors or differences. MBE describes the direction (+/-) of the error or difference bias.

The overall uncertainty was also calculated using a method similar to that described in Habte, Sengupta, and Lopez (2017) by assuming the measurement uncertainty of 5%:

$$|U_{95}| = 2 * \pm \sqrt{\left(\frac{U_{\text{meas}}}{2}\right)^2 + \left(\frac{\text{MBE}}{2}\right)^2 + \left(\frac{\text{RMSE}}{2}\right)^2}$$

where U_{meas} is the estimated uncertainty of the ground measurements, and MBE and RMSE are derived from the methods shown here. As reported in Habte, Sengupta, and Lopez (2017), Habte et al. (2014), and Reda (2011), the expanded uncertainties—such as U_{meas} , MBE, and RMSE—have a normal distribution; therefore, these values are divided by 2 (coverage factor) to obtain the standard uncertainty. However, the U_{95} method overestimates uncertainty because RMSE includes the bias error, which is causing a double counting of errors. Future studies will investigate to find better statistical metrics that assist in quantifying the overall uncertainty.

2 Meteosat-8 Maps

Figure 3 shows GHI and DNI maps for the Meteosat-8 domain for 2017–2019. Most of India demonstrated between 4.5–5.5 kWh/m²/day for GHI and DNI.

Figure 3. GHI (left panel) and DNI (right panel) maps for the Meteosat-8 domain

3 India Maps

India solar resource data at a 4-km by 4-km spatial and 15-minute temporal resolution were also created (Figure 4). The data include the three solar irradiance components—GHI, DNI, and diffuse horizontal irradiance (DHI). Moreover, the data include other ancillary meteorological parameters, such as temperature and wind speed. These ancillary data sets were obtained from the Modern-Era Retrospective Analysis for Research and Applications, Version-2 (MERRA-2), from the National Aeronautics and Space Administration (Bosilovich, Lucchesi, and Suarez 2016). Spatial and temporal interpolation methods were employed to downscale the MERRA-2 data sets, which are available at an hourly temporal and approximately 50-km by 50-km spatial resolution to the same space and time resolution of the Meteosat-8 grid (4 km by 4 km for every 15 minutes).

Figure 4. GHI (left panel) and DNI (right panel) maps for India

4 Validation Result

Figure 5 shows the correlation between the satellite-derived data set and the ground measurement for the 10 locations. For all sites, clear-sky conditions demonstrated good agreement relative to the cloudy skies.

Figure 5. Correlation between the satellite-derived data set and ground observations

The satellite-derived data for the India locations demonstrated overestimation (positive bias) (Figure 6). This could be because of (1) the solar geometry issue of the Meteosat-8 satellite where these locations are far east of the viewing angle of the satellite and/or (2) the uncertainty of the ground measurement, which could be higher than normal.

Figure 6. MBE in percentage for 2017–2019 data

MAE and RMSE statistics were also analyzed (Figure 7). The locations in Europe and India demonstrated higher MAE, and the same reasons that were described for higher MBE apply here.

Figure 7. MAE (top) and RMSE (bottom) in percentage for 2017–2019 data

For GHI, the India BSRN locations demonstrated 20%–30% overall uncertainty ($|U_{95}|$). As shown in Figure 8, the uncertainty estimation is higher for the hourly data, and as the time average increased, the uncertainty decreased and approached the ground measurement uncertainty of 5%.

Figure 8. GHI overall uncertainty in percentage for 2017–2019 data

5 Data Access

The data set can be accessed directly from <https://nsrdb.nrel.gov>, then from the main web page, select [NSRDB Viewer](#). From the top left menu, select “download data,” and select the desired location or area by placing the cursor in the Meteosat domain area. A request will pop up for a “Data Download Information Form”; please fill in some personal information, such as name and email. Next, as shown in Figure 9, a window to select the desired data set will pop up. Select the desired parameter(s) and year(s), then the data will be emailed to your inbox.

The data can also be accessed programmatically using an application programming interface. Users can refer to <https://developer.nrel.gov/docs/solar/nsrdb/> for instructions.

Data Download Wizard

PSM v3 5 Minute PSM v3 Puerto Rico SHR SUNY India TMY Spectral TMY India SUNY India

MSG IODC: PSM v3 Spectral On-demand PSM v3 TMY

METEOSAT IODC Region: Physical Solar Model (PSM)

The [National Solar Radiation Database \(NSRDB\)](#) is a serially complete collection of satellite-derived measurements of solar radiation—global horizontal, direct normal, and diffuse horizontal irradiance—and meteorological data. These data have been collected at a sufficient number of locations and temporal and spatial scales to accurately represent regional solar radiation climates.

The Indian Ocean Data Coverage of the Meteosat satellite covers India and its surrounding regions. The Physical Solar Model Version 3 (PSM-v3) was used to develop these datasets. The 4km x 4km data is provided at a 15 minute resolution.

[Documentation](#)

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[Contact](#)

Select Years [Select All](#) [Clear All](#)

☐ 2017 ☐ 2018 ☐ 2019

Select Attributes [Select All](#) [Clear All](#)

The minimum required attributes for the SAM PV and CSP models have been selected by default.

☒ Temperature	☐ Clearsky DHI	☐ Clearsky DNI
☐ Clearsky GHI	☐ Cloud Type	☒ Dew Point
☒ DHI	☒ DNI	☐ Fill Flag
☐ GHI	☒ Relative Humidity	☐ Solar Zenith Angle

Select Download Options [Select All](#) [Clear All](#)

☐ Include Leap Day ☐ Convert UTC to Local Time **Select Interval (Minutes)**

Download Limit Indicator

[Edit User Info](#) [Download Data](#)

Figure 9. Data download wizard to access National Solar Radiation Database data

6 Summary and Future Work

High-volume solar resource and meteorological data sets at a 4-km by 4-km spatial and 15-minute temporal resolution were developed using Meteosat-8 satellite data for India and surrounding countries. The data can be used in various solar energy project phases, from prefeasibility to operation and management.

The data were validated using high-quality ground measurement data obtained from the BSRN network. Overall, the observed uncertainty was less than 20% for the African BSRN locations and 30%–35% for the India and European locations. The higher uncertainties for the latter locations could be a result of the satellite viewing geometry limitations.

For future work, to understand long-term irradiance variability, adding more years to the 2017–2019 data set is recommended because understanding long-term variability will assist in the design and operation of solar energy conversion systems.

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