# Clear Sky Irradiance Year-to-Year Variations and Trends

## Preprint

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# Clear Sky Irradiance

# Year-to-Year Variations and Trends

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***Abstract*—Solar radiation data for seven SURFRAD stations for the period 1996-2018 show an increase in irradiance under clear skies over the period, but the increase was not constant and shorter periods may have even experienced decreases in irradiance.**

***A popular implementation of a clear sky model provided modeled irradiances for comparison with the SURFRAD data under conditions screened for clear skies. The use of the clear sky model, which did not consider year-to-year variances in atmospheric turbidity, was found problematic for resolving small changes in irradiance important for determining PV system degradation over three or five years, but less problematic for a period of ten years.***

***Keywords—Irradiance, clear-sky, model, data, aerosols.***

## I. Introduction

The performance of a photovoltaic (PV) system is primarily determined by the amount of solar radiation received in the plane of the PV modules, which is generally referred to as the plane-of-array irradiance (POA). With knowledge of the POA and other factors, the electrical output of the system may be assessed as to whether expectations are met, and changes in performance over time from degradation effects may also be determined.

The POA may be measured with pyranometers, but accuracy will suffer if the pyranometer is not regularly cleaned and calibrated, or otherwise maintained. Consequently, a method was developed to evaluate PV system performance using a modeled clear sky POA ($POA_{cs}$) [1]. The $POA_{cs}$ is modeled using the Ineichen clear sky irradiance model [2] and monthly Linke turbidity coefficients. Linke turbidity coefficients encompass the effects of both aerosols and water vapor. For clear sky models, aerosols are the dominating factor that affects the accuracy of the model, but, unfortunately, reliable aerosol data are extremely limited [3]. Consequently, [1] uses the same Linke turbidity coefficients for all years.

However, both solar radiation and aerosol amounts vary year to year and long-term trends are also evident. Widespread dimming (decreased solar radiation) was observed between the 1950s and 1980s and then followed by brightening (increased solar radiation) [4]. In Greece, the observed brightening for the period 1980-2012 was determined to be +1.5% decade$^{-1}$, which was less than for other parts of Europe, and attributed mostly to changes in aerosol amounts [5].

Man-made effects are evident. Because of the 1990 Clean Air Act Amendments, U.S. $SO_2$ emissions declined by over 70% between 1995 and 2013, coinciding with observed aerosol reductions of 3% year$^{-1}$ [6]. Increasing trends in clear sky diffuse radiation may be due to more high-level cirrus clouds from increasing air traffic over the U.S. [7].

This work assesses the year-to-year and long-term variations in the clear-sky irradiance by comparing measurements from the Surface Radiation budget (SURFRAD) network with those modeled with a clear sky model that uses the same model inputs for all years.

## II. Approach

### *A. Measured Data*

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 [8]. The stations are located near Bondville, IL; Boulder, CO; Desert Rock, NV; Fort Peck, MT, Goodwin Creek, MS; Penn State University, PA; and Sioux Falls, SD.

Data used for this work includes the global horizontal irradiance (GHI), the direct normal irradiance (DNI), the diffuse horizontal irradiance (DHI), and the ground-reflected irradiance (GRI) for determining albedo. Depending on when the station was deployed, we used data from as early as 1996 and through 2018. Prior to 2009, the temporal resolution of the data is 3 minutes. For 2009 and after, the temporal resolution provided is 1 minute. For consistency when screening data, we reformatted 2009 and later as 3-minute resolution data files.

### *B. Modeled Data*

For the same locations and times of the SURFRAD data, clear-sky values of GHI, DNI, and DHI were modeled using the PVLIB-Python v0.6.4 implementation of the Ineichen model [9].

### *C. POA and $POA_{cs}$*

For the same locations and times, POA and $POA_{cs}$ were determined for a south-facing latitude tilt PV array using the Perez tilted surface model [10]. The Perez model is an improved and refined version of their original model that was recommended by the International Energy Agency for calculating solar radiation for tilted surfaces [11].

For POA, the SURFRAD measured values of DNI, DHI, and albedo were input to the Perez model. For $POA_{cs}$, the Ineichen modeled values of DNI and DHI and an albedo of 0.2 were input to the Perez model.

### D. Data Screening

Data were screened using the method of [1] (POA > 200 W/m$^2$ and within ±15% of $POA_{cs}$) and with a method to detect clear-sky periods from measured GHI time-series data [12]. The clear-sky periods detected meet statistical criteria representative of clear skies. Clouds may be present, but likely would not be interfering with the DNI. The clear-sky periods were detected using a PVLIB-Python v0.6.4 implementation of the Detect Clearsky model. Standard defaults were used, except for the sliding window time which was increased from 10 minutes to 15 minutes to better accommodate the use of 3-minute time series data.

An example of the clear-sky periods detected is show in Fig. 1 for Boulder, CO on June 1, 2006. Times of the clear skies detected are represented by the red line and times detected as not having clear skies are represented by black x's. Except for a few disturbances in the morning, the Detect Clearsky model indicated that skies were clear until about 2:00 pm, not clear from then until about 6:00 pm, and then followed by a brief period of clear skies before sunset. This would be a typical day for Boulder for that time of year, clear mornings followed by partly cloudy skies in the afternoon.

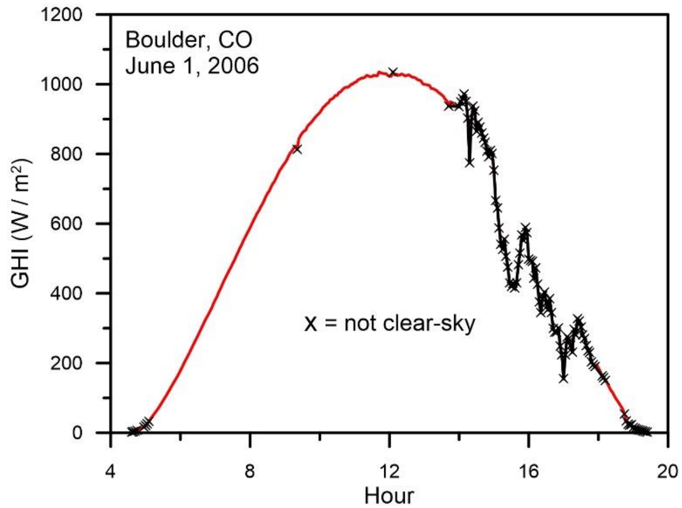


Fig. 1. Clear-sky periods detected by the Detect Clearsky model for Boulder, CO for June 1, 2006. Black x's represent times when determined to have skies that were not clear.

## III. RESULTS

For each year and location, POA and $POA_{cs}$ data for times meeting the screening criteria were summed to provide annual totals. The annual totals for POA were divided by that for $POA_{cs}$ to provide the ratios $POA/POA_{cs}$. Ratios greater than one indicate that POA sums derived from SURFRAD measurements were greater than $POA_{cs}$ sums derived from modeled clear-sky data, and vice versa. Fig. 2 show the ratios by year and station. In general, annual $POA_{cs}$ was within 5% of POA and there is an increase in POA relative to $POA_{cs}$ over time.

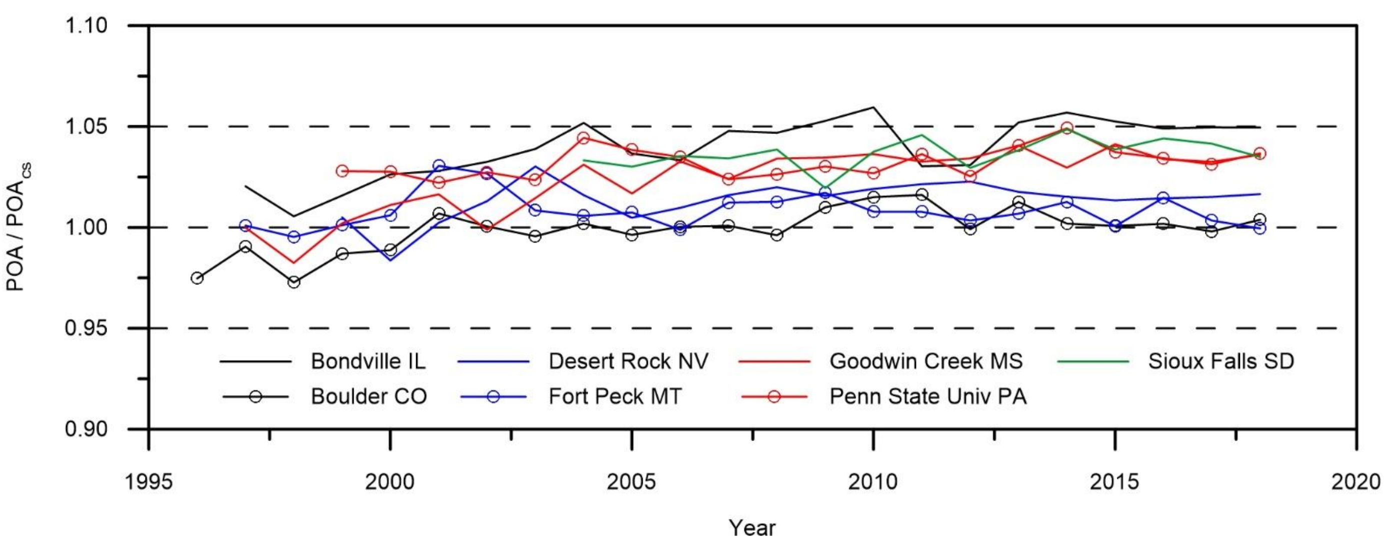


Fig. 2. Ratios of annual sums of POA to $POA_{cs}$ for the seven SURFRAD stations for data meeting the clear-sky screening criteria.

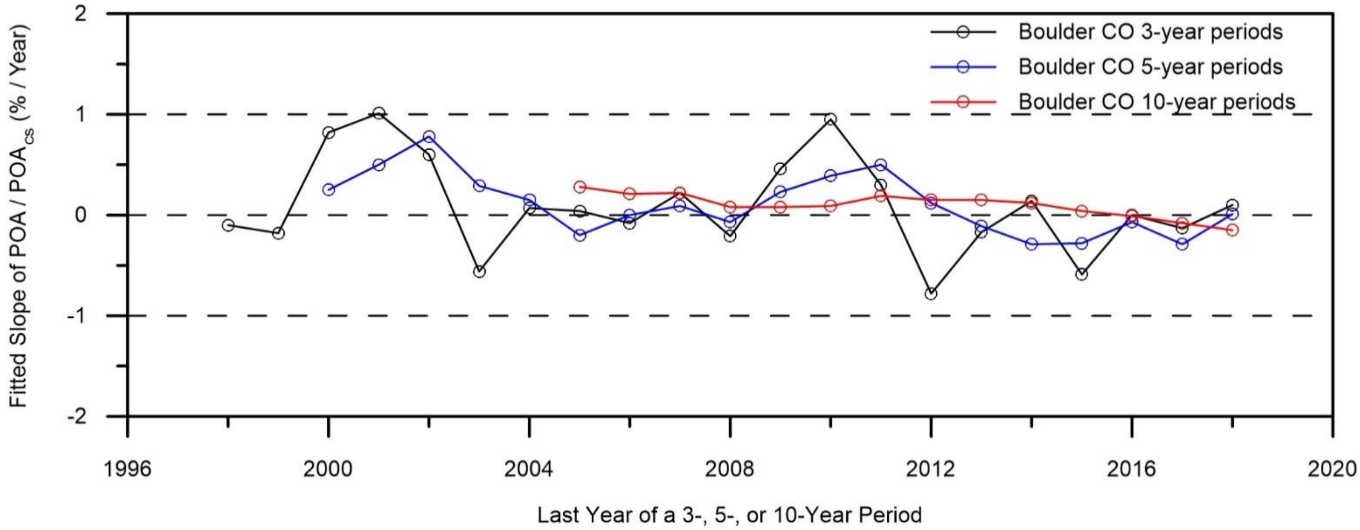


Fig. 3. Fitted slopes of the POA to POA$_{cs}$ ratios for 3-, 5-, and 10-year periods for Boulder, CO.

TABLE I. 95% CONFIDENCE INTERVALS FOR POA$_{CS}$ REPRESENTING YEAR-TO-YEAR TRENDS IN POA FOR 3-, 5-, AND 10-YEAR PERIODS

| Station | 95% Confidence Interval (±%) | | |
|---|---|---|---|
| | *3-Year* | *5-Year* | *10-Year* |
| Bondville, IL | 1.44 | 0.80 | 0.40 |
| Boulder, CO | 0.96 | 0.62 | 0.30 |
| Desert Rock, NV | 1.22 | 0.72 | 0.22 |
| Fort Peck, MT | 1.24 | 0.78 | 0.12 |
| Goodwin Creek, MS | 1.14 | 0.60 | 0.50 |
| Penn State Univ, PA | 0.98 | 0.58 | 0.18 |
| Sioux Falls, SD | 1.06 | 0.36 | 0.22 |

We performed linear least-squares fits of the ratios versus year to determine the slope (% / year) for periods that might be used for evaluating PV system performance – 3, 5, and 10 years. (For three-year periods, this includes separate fits for 1996-1998, 1997-1999, 1998-2000, and so on). The fitted slopes for Boulder, CO are shown in Fig. 3. Slopes are closer to zero for the longer periods. Non-zero slopes may be problematic for assessing PV performance over time using POA$_{cs}$ because actual degradation may be greater or less than determined. (POA$_{cs}$ represents the case where turbidity and clear-sky irradiance levels do not change from year to year).

95% confidence intervals for the fitted slopes were determined as twice the root-mean-square difference between the fitted slopes and zero. These values are shown in Table I for the three period lengths and for each location. A longer period improves the confidence interval.

## IV. ANALYSIS AND DISCUSSION

For the period 1996 – 2018 and the SURFRAD stations, the clear sky irradiance increased a few percent, presumably from the long-term reductions in aerosols or turbidity from factors such as discussed in the Introduction. The clear sky modeling would not indicate changes in irradiance because the same Linke turbidity coefficients were used for all years.

Year-to-year relative changes in POA and POA$_{cs}$ can be either positive or negative, depending on the year-to-year changes in actual turbidity. For evaluating PV degradation using POA$_{cs}$, if the actual POA is increasing over time, this will mask the actual PV degradation, and vice versa. A more significant error is likely to occur for shorter evaluation periods. From Table I, only the 10-year periods have 95% confidence intervals for POA$_{cs}$ that are less than what are generally recognized as the median degradation rates for x-Si technologies – 0.5-0.6%/year [13].

Modeling POA$_{cs}$ would have been even less favorable if there had been any significant volcanic eruptions during the data collection period, such as the eruption of El Chichon in 1982 or Mount Pinatubo in 1991. These effects were felt worldwide with peak reductions of DNI of 20% and GHI of 10%, and for an extended time. Atmospheric aerosols resulting from Mount Pinatubo diminished the solar irradiance for 3½ years [14].

## V. SUMMARY

Analysis of solar radiation data for seven SURFRAD stations for the period 1996-2018 showed an increase in irradiance under clear skies over the period, but the increase was not constant and shorter periods may have even experienced decreases in irradiance.

Possible explanations for the increase are the reductions in emissions due to the 1990 Clean Air Act and an increase in high-level cirrus clouds from increased air traffic.

Present-day clear sky modeling practices as applied to PV system performance will not detect these changes in irradiance under clear skies. This may be problematic for analyzing small changes, such as PV system degradation over three or five years, but less problematic for a period of ten years.

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