CLEAR SKY DETECTION MODELS: A COMPARATIVE ANALYSIS

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Abstract

Brazil is currently experiencing a substantial expansion of photovoltaic plants, which requires evaluating their performance under stable irradiance conditions and early failure detection. Clear-sky detection models are vital for distinguishing clear from cloudy periods. This work aims to analyze clear-sky detection models. For the tests, data from REDESOLPE GHI at the Araripina station were used, 142 periods were previously identified and manually classified as clear or cloudy, serving as a reference to verify the detection capability of the criteria. The analyzes were divided into: C1 and C2 of Galdino et al. for each criterion individually, C1 and C2 of this article for each criterion individually, and C1 and C2 of Galdino et al. for the combination of criteria. Based on the results, we observed that some clear-sky detection criteria stand out, and it was also possible to determine that adjusting the clear-sky model constants had no significant effect on the results, making adjustment unnecessary. The consequences are: reduced analysis time and widespread use of the models.

Keywords: *Clear sky detection criteria, Clear sky models, Photovoltaic solar, Solar energy, Solar radiation.*

1. Introduction

Nowadays, there is a growing demand for means of generating renewable energy in Brazil. It's necessary,taking into account the need to reduce damage caused to the environment from non-renewable sources. As a result, photovoltaic applications are increasingly expanding, and it is necessary to stay tuned to some important points to implement this type of generation, for example, analyzing the appropriate solar resource permit so that the local radiation profile can be studied and the energy generation and its possible failures predicted (Galdino et al., 2016).

It is possible to obtain an irradiance profile under stable conditions on a clear day, with which some faults present in photovoltaic plants can be found out. The sky with the presence of clouds influences the irradiance values, which may, for example, cause its reduction or increase due to the cloud edge effect. There are two situations that can be considered a clear sky: a cloudless sky in which the whole firmament is without the presence of clouds, which is called the clear sky, and the Sun cloudless, which is characterized by no clouds covering the solar disk (Gueymard et al., 2019).

The detection model by Reno and Hansen (2016), for example, is based on the use of five clear sky identification criteria, and they all follow an analysis premise, a time window of 10 minutes, in order to identify that period as clear or cloudy. It is therefore important to identify periods of one or several days in which there is a clear sky, because with it, we can observe the quality of the radiation data, detect failures in photovoltaic modules, as well as analyzing their performance, etc (Bright et al., 2020).

This work analyzed the performance of the five criteria initially individually for each clear sky detection criterion and later jointly by combining the criteria, thus verifying that the combination of the five criteria obtained less efficiency in relation to some criteria that individually presented better detection results. For the individual analyses, C1 and C2 from Galdino et al. were used, and then C1 and C2 from this paper, and thus it was found, when aiming at the detection results, that the adjustment of C1 and C2 can be dispensed with.

10.18086/swc.2025.03.10 Available at http://proceedings.ises.org

2. Methodology

2.1 Clear sky models

According to Joplim et al. (2016), clear sky models are procedures that allow estimate irradiance values on a specific day, time and location for a cloudless condition. There are physical and empirical models, an empirical model developed by Salazar, Hernández and Saravia (2010) was used in this work and the constants (C1 and C2) were obtained from the proposed model by Joplim et al. (2016), due to the proximity between Araripina (Northeast Brazilian city) used for tests of this project, and Petrolina used to develop the Joplim model.

The intensity of radiation, on a cloudless day, is the result of absorption and dispersion that are related to the passage of radiation through the atmosphere. The Air Mass (AM) will influence the results, this was observed and considered by Salazar, Hernández and Saravia (2010). So they proposed the Equation eq. 1 to calculate Kt which is the quotient between the global horizontal irradiance (GHI) and extraterrestrial irradiance (G0), where C1 and C2 are constants relative to the location.

$$\frac{GHI}{G0} = C_1^{AM^{C_2}} \quad \text{(eq. 1)}$$

To discover the GHI value, initially the G0 value is calculated following the Equation eq. 2 which has as input parameters: the Zenital angle (θ_Z) and the Julian day (d).

$$G0 = 1367[(1 + 0.033cos(\frac{2\pi}{360}(d-2)))cos\theta_z] \quad \text{(eq. 2)}$$

For the initial tests, the constants used were provided by Joplim et al. (2016) due to the proximity between the cities of Araripina and Petrolina (200 km). After that, it was also tested constants obtained from Araripina local measured data (Kt) and AM (geometric value) using the SciDAVis software. All days present between January to July were chosen, totaling 212 days, the graph of Kt X AM was plotted, making it possible to observe points that can be putted away, making the results more accurate.

The process for detecting clear skies requires an initial definition of clear sky model, which produces an irradiance profile of a cloudless sky day, as shown in Figure 1, so that it is possible to make a comparison between the clear sky model and the measured irradiance data (GHI). There are several detection models that use different input information so that identification is possible. Gueymard et al. (2019) listed 15 models and organized the input information. For instance, the model described by Ineichen (2016) requires input data such as: zenith angle, extraterrestrial irradiance, global horizontal irradiance, direct normal irradiance, diffuse normal irradiance and depth aerosol optics.

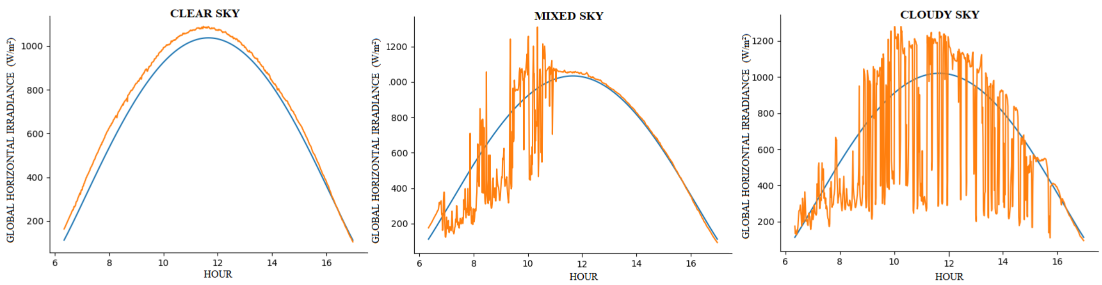

Figure 1: Profile of different cloud conditions. The green lines represent the clear sky model, and the orange lines are the GHI measurements. There is high variability due to the presence of clouds in the sky. The GHI follows the clear-sky model profile on a clear-sky day or moment.

The model proposed by Reno and Hansen (2016) that needs only GHI and clear sky GHI (GHIcs) was used in this work due to the availability of GHI data in all stations of the REDESOLPE (Pernambuco Solarimetric Network that comprises 75 solar stations). The authors described 5 criteria for clear sky identification: mean

GHI value (MV), maximum GHI value (MaxV), line length (LL), deviation pattern of rate of change in irradiance (also called standard deviation) (SD) and maximum difference between changes in GHI and clear sky time series (MD). All equations below are valid for both GHI and GHIcs.

1 - Mean GHI value (MV): This criteria compares the GHI mean $(\overline{G})$ with GHIcs mean and uses the Equation eq. 3, where n is the number of analyzed values.

$$\overline{G} = \frac{1}{n}\sum_{i=1}^{n} GHI_i \tag{eq. 3}$$

2 - Maximum GHI value (MaxV): the mean of GHI and GHIcs values may be close without the influence of clouds, that´s why this criterion observes the maximum values of GHI and GHIcs and compares them using Equation eq. 4.

$$M = max[GHI_i], \forall i \in (1, 2, ..., n) \tag{eq. 4}$$

3 - Line Length (LL): The basis of this criteria is the variability of the line sections that connect the GHI time series (Equation eq. 5).

$$L = \sum_{i=1}^{n-1} \sqrt{(GHI_{i+1} - GHI_i)^2 + (t_{i+1} - t_i)^2} \tag{eq. 5}$$

4 - Standard deviation of the rate of change in irradiance (SD): This criteria analyzes the standard deviation in sequences of a time series. It uses: Equation eq. 6 which calculates the slope (S) of a straight line between two measured values, Equation eq. 7 which calculates the average of the slope (S) $(\overline{S})$ and Equation eq. 8 which calculates the standard deviation (σ) where $\overline{G}$ is the mean irradiance.

$$S_i = \frac{GHI_{i+1} - GHI_i}{t_{i+1} - t_1}, \forall i \in (1, 2, ..., n-1) \tag{eq. 6}$$

$$\overline{S} = \frac{1}{n-1}\sum_{i=1}^{n-1} S_i \tag{eq. 7}$$

$$\sigma = \frac{1}{\overline{G}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n-1}(S_i - \overline{S})^2}} \tag{eq. 8}$$

5 - Maximum difference between changes in GHI and the clear sky time series (MD): This criteria is based on the analysis of variation in sequential GHI measurements compared with GHIcs. Equation eq. 9 calculates the difference between GHI data (Xi), Equation eq. 10 obtains the difference between GHIcs data (Xcs) and finally Equation eq. 11 exposes the maximum difference (X).

$$X_i = GHI_{i+1} - GHI_i, \forall i \in (1, 2, ..., n-1) \tag{eq. 9}$$

$$X_{i,CS} = GHI_{i+1,CS} - GHI_{i,CS} \tag{eq. 10}$$

$$X = max(|X_i - X_{i,CS}|) \tag{eq. 11}$$

2.2 Implementation of the Criteria

The clear sky model and the aforementioned criteria were implemented using the Python programming language. The first tests were carried out C1 and C2 from Galdino et al.. It was analyzed all days of 2022, observing how each model behaves, thus it was possible to analyze the particularities of each one such as, which one has better accuracy for different sky conditions: clear sky, cloudy sky and a day when both situations occurred (Figure 1).

In a later stage, the tests of the detection criteria used the same model of clear skies with the constants C1 and C2 adjusted for the test site. The results of this adjustment will be shown later.

3. Results and discussions

The analyses were divided into stages:

1 - C1 and C2 from Galdino et al.,

2 - C1 and C2 from this paper,

3 - Result comparisons.

A graph for each day was created for each Clear Sky detection criteria with two curves (GHI measurement and Clear Sky model), dots over the curve indicate when the criteria identified the clear sky. This graph structure allows to analyze each criteria response individually, and facilitate evaluations.

3.1 C1 and C2 from Galdino et al.

The values of the C1 and C2 constants used in this stage were 0.726 and 0.409, respectively (JOPLIM et al., 2016). It was possible to observe by carrying out the analysis with all the classification criteria that some of them identified the clear sky, presenting a better response than others. This means that the criteria indicate a clear sky when really it is that one. On the other hand, some criteria when evaluating the sky with clouds presented a wrong response, identifying these conditions as clear skies incorrectly. The red circles highlight this situation in Figure 2.

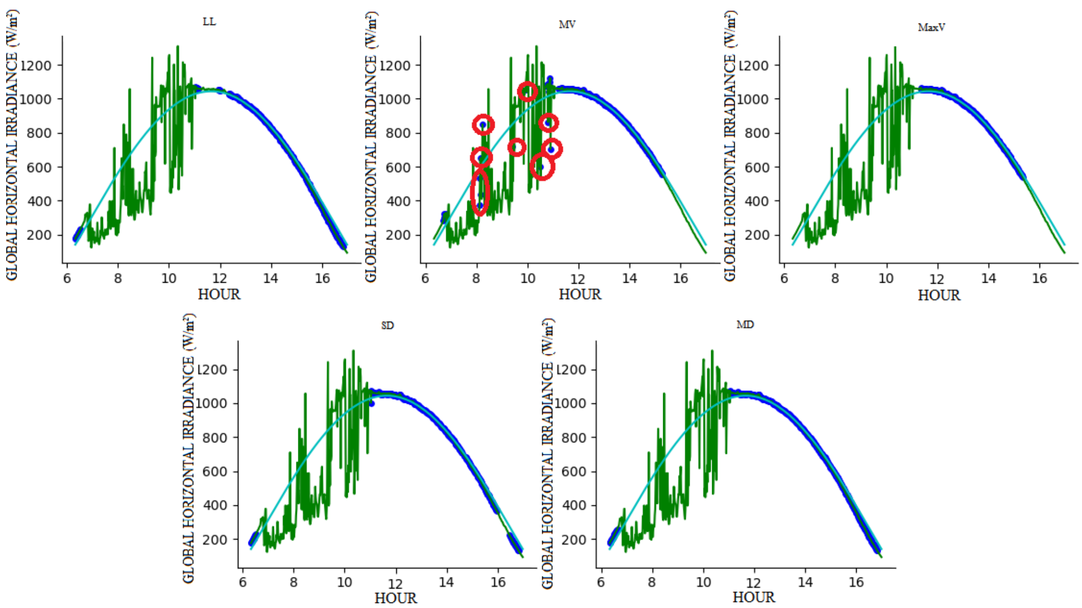

Figure 2: Example of clear sky identification criteria without C1 and C2 constants adjustment.

3.2 C1 and C2 from this paper

The adjustment of the constants was carried out using the relation between Kt and AM calculated (Figure 3 only in the moments of clear sky identified and manually confirmed in the first stage (Figure 2). What allowed, with the aid of SciDAVis software obtaining the new constants.

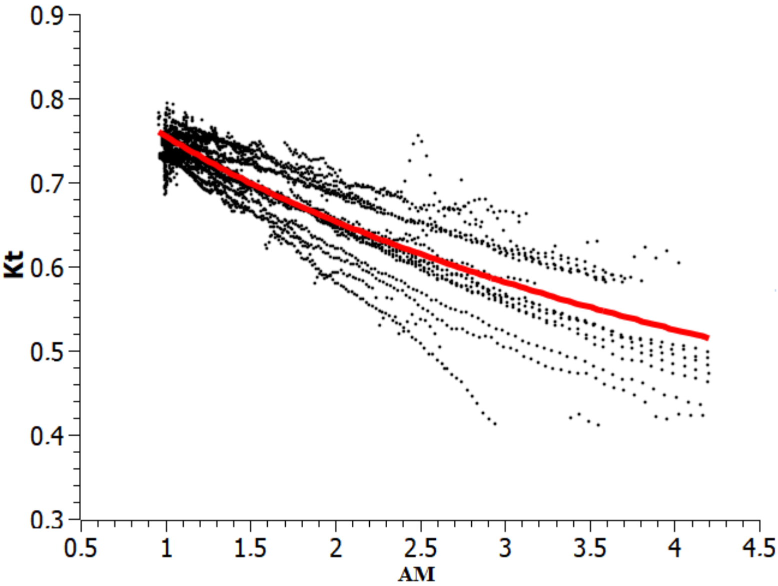

Figure 3: Scatter chart of Kt x AM. Black point are related to clear sky measurements and the red line is the curve obtained from linear regression with the Equation eq. 1

The process described in the previous stage was repeated now, using the new C1 and C2, which are 0.75 and 0.594, respectively. The Figure 4 shows the result for the same day presented in the Figure 2. It can be noted, comparing these two figures, that the changes were imperceptible on that day for LL, MV, MD and SD criteria. The MaxV criteria recognized the measurements after 15 h as clear sky that weren't previously recognized and unrecognized a small piece of time near midday. The results for all days will be shown later.

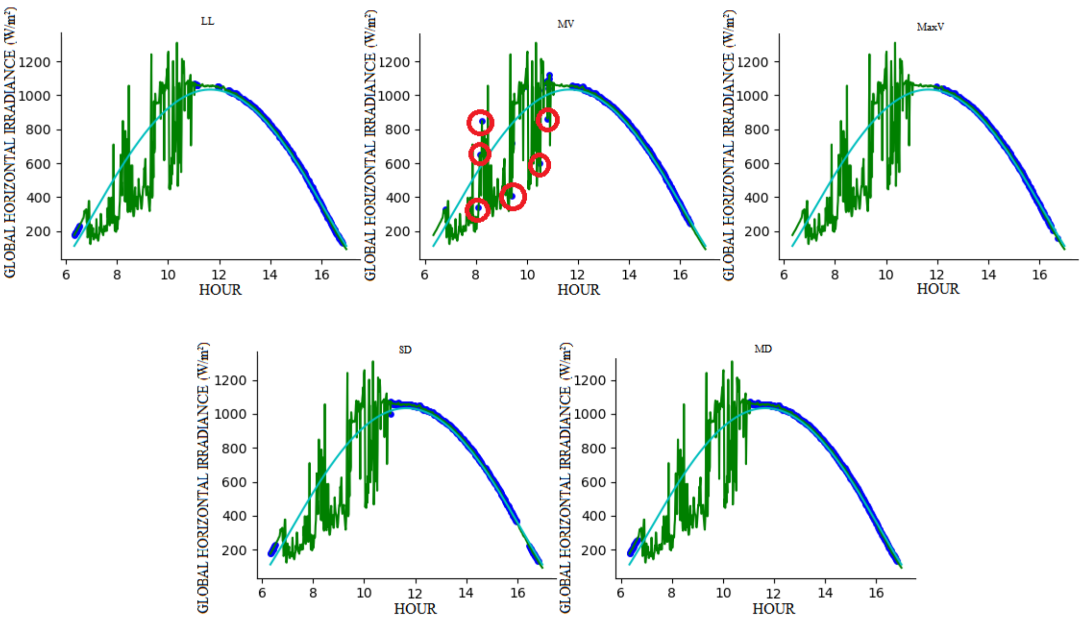

Figure 4: Example of all clear sky criteria using obtained constants in the clear sky model.

3.3 Result comparisons

The January, July and October months were chosen for comparisons of all criteria due to their climate conditions. January is a cloudier month, July has mixed periods (with and without the presence of clouds), and October is mainly a cloudless month.

The clear sky detection model proposed by Reno and Hansen (2016), which requires only the GHI and the clear sky GHI (GHIcs), was used in this work, the authors described five criteria for identifying clear skies: MV, MaxV, LL, SD, MD. These comparisons visually identified 142 periods, which were classified in a new way: CSC (Confirmed Clear Sky), CDC (Confirmed Cloudy Sky), CSNC (Unconfirmed Clear Sky), and CDNC (Unconfirmed Cloudy Sky). An ideal criterion should have 100% of CSC and CDC and 0% of CSNC and CDNC. It is important to note that the term cloudy sky is being used for any type of advent, which can be a cloudy sky itself, partly cloudy, or shadowing caused by objects. The four indicators were calculated for the five criteria listed above and compared under three conditions: C1 and C2 from Galdino et al. for each criterion individually, C1 and C2 from this paper for each criterion individually, and the combination of these criteria with C1 and C2 from Galdino et al..

All results are showed in 5.

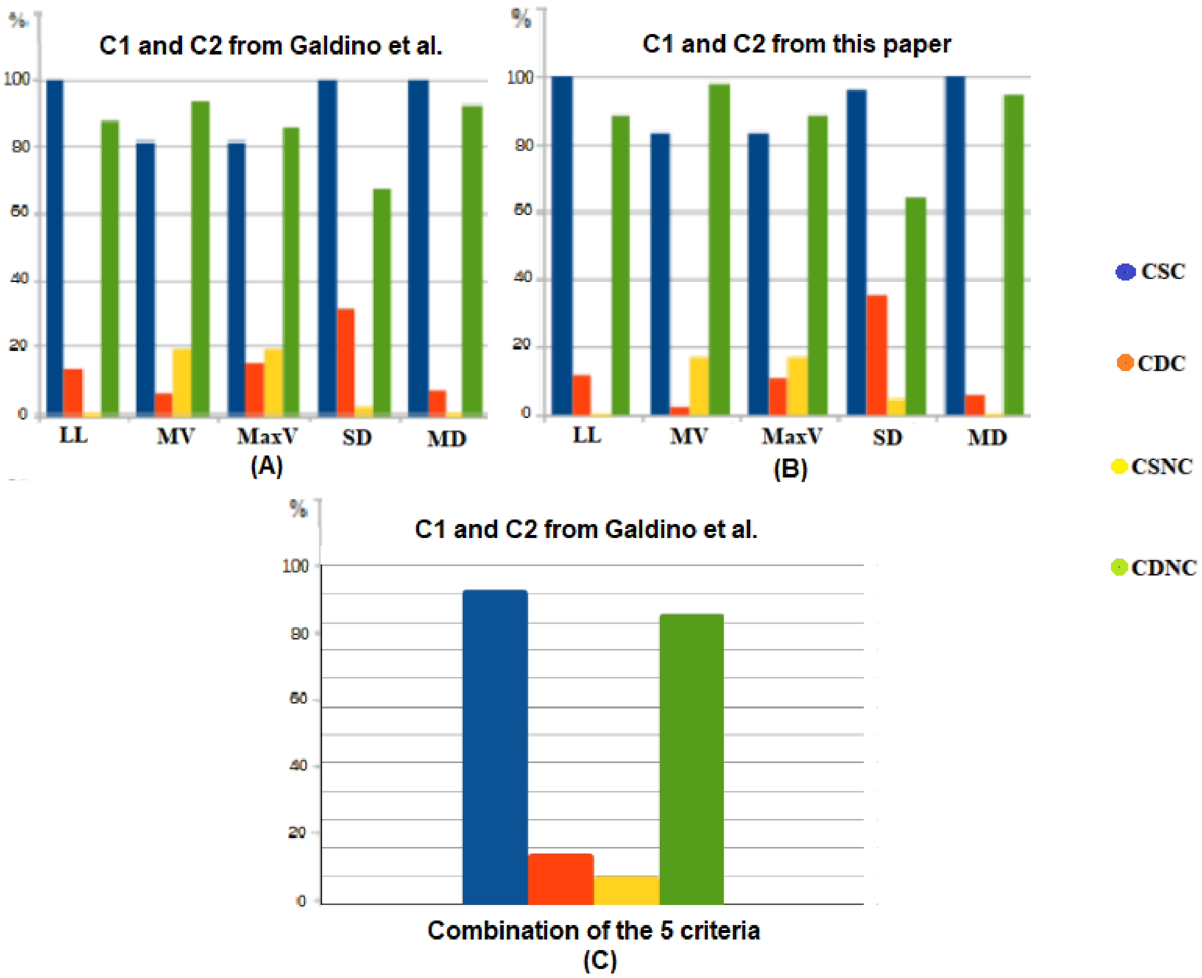

Figure 5: Comparisons between the condition of adjust, non adjusted constants.

The detection performance for CSC periods under all criteria exceeded 80%, indicating that all criteria individually (Fig5. A and B) and also combined (Fig5. C) were able to correctly identify the clear sky condition in more than 80% of the cases. Notably, the LL, SD and MD criteria (Fig5. A) achieved 100% accuracy in this aspect. In contrast, the LL, MV, MaxV and MD criteria (Fig5. A and B) presented accuracy below 20%

for the CDC indicator, meaning that they correctly identified cloudy skies in less than 20% of the cases. The SD criterion (Fig5. A and B) obtained a score higher than 30% in this indicator regardless of the C1 and C2 used. In summary, the criteria individually are highly reliable for detecting clear skies, but present significant difficulties in identifying cloudy skies (CDC).

The use of the new constants C1 and C2 resulted in a slight improvement in the detection of cloudy skies, but nothing very significant. The SD and MaxV criteria (Fig5. A and B) increased only 4.2% and 4.3% in the CDC indicator, respectively. In this case, adjusting the constants did not have the expected impact on the results. When combining the 5 criteria (Fig5. C), it was possible to observe a 7.5% reduction in CSC detection, compared to the individual use of the LL and MD criteria (Fig5. A). It was also observed that the SD criterion (Fig5. A) individually detected approximately 45% more CDC compared to the combined criteria (Fig5. C).

With this combination of the 5 criteria, it is possible to see a decrease in detection efficiency.

4. Conclusion

A clear-sky model was used with its five criteria for clear-sky detection. It was observed that these criteria have two aspects: a clear sky must be identified, and a cloudy sky must also be correctly detected. An ideal model should achieve 100% in both situations. Tests with the five criteria were performed to identify quality indicators that reflect the described capability. First, it was observed that the empirical clear-sky model does not significantly influence the quality of the criteria.

Its constants or the effort to constantly adjust them do not increase their quality. This does not mean that it is not necessary, resulting in reduced analysis time and widespread use of the models. This does not mean that it is not necessary, but if the model provides some constants, they can be used.

By combining the five criteria, a decrease in detection efficiency can be observed, making it more feasible for this article to use the criteria that individually performed best. In particular, the LL and SD criteria stand out among the others, as they obtained better identification of clear and cloudy skies.

It was observed that the weak point of all criteria is the detection of cloudy skies, the implementation of improvements to alleviate this failure in the detection of cloudy skies is a necessary measure to further improve the criteria.

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