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Characterization of the intraday variability regime of solar irradiation of climatically distinct locations

Philippe Lauret [a,*], Richard Perez [b], Luis Mazorra Aguiar [c], Emeric Tapachès [a], Hadja Maimouna Diagne [a], Mathieu David [a]

[a] *Laboratoire de Physique et Ingénierie Mathématique pour l'Energie et l'environnement (PIMENT), University of La Réunion, Campus du Moufia 15, Avenue René Cassin, 97715 Saint Denis Messag 9, France*

[b] *ASRC, The University at Albany, SUNY, United States*

[c] *University Institute for Intelligent Systems and Numerical Applications in Engineering, University of Las Palmas de Gran Canaria, Edificio Central del Parque Tecnológico, Campus de Tafira, 35017 Las Palmas de Gran Canaria, Spain*

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Abstract

This paper investigates the relationship between two parameters characterizing a given location on a given day: the daily clear sky index KT^* and the intraday variability given by the standard deviation of the changes in the hourly clear sky index $\sigma(\Delta kt^*_{\Delta t})$. Empirical evidence assembled from twenty climatically distinct locations led us to derive a simple model to infer intraday variability from the day's clear sky index. Although the model shows little dependence on location, we did observe a systematic difference traceable to a location's prevailing cloud formation regime. Therefore, we also propose two alternative models for sites where cloud formations is influenced by local orography and sites where cloud formation is traceable to weather events only. Finally, we present a possible application of the models to enhance the informative content of day(s) ahead NWP forecasts.
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1. Introduction

The characterization of solar resource variability is an important issue for grid-connected solar PV as penetration increases because of the challenges variability poses to grid operators (Perez and Hoff, 2013).

The topic of solar energy variability has generated a considerable amount of research during these last years. In particular, much attention has been paid to the study of the short-term variability of the PV power output of a single plant due to the cloud fluctuations (Hansen, 2007; Marcos et al., 2011; Mills et al., 2010; Perpiñán et al., 2013; Van Haaren et al., 2014).

Some authors (Perez and Hoff, 2013; Lave et al., 2012; Sengupta and Keller, 2011; Murata et al., 2009) also showed that short-term power fluctuations generated by an ensemble of geographical dispersed PV plants are considerably reduced compared to a single one, and that the reduction can be predicted on the basis of power plant interdistance, cloud or cloud system motion and considered fluctuation time scale.

Metrics describing and quantifying variability at different time scales are a key ingredient of this characterization.

* Corresponding author. Tel.: +262 692 67 48 07; fax: +262 262 93 86 65.

E-mail address: philippe.lauret@univ-reunion.fr (P. Lauret).

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Van Haaren et al. (2014) proposed a quantitative metric called the Daily Aggregate Ramp Rate (DARR) which sums 1-min single Plane Of Array (POA) irradiance sensor over each day to characterize daily variability in a utility-scale plant. Lenox and Nelson (2010) proposed the Inter-Hour Variability Score (IHVS) which summed the absolute value of 1-min changes in POA irradiance and AC power output in each hour. Badosa et al. (2013) showed that solar irradiance variability at the diurnal scale can be classified in regimes based on three parameters. These parameters are the daily clear-sky index, solar irradiance morning–afternoon asymmetry and random variability of the solar irradiance.

In a previous work, Perez et al. (2011) proposed models to characterize the one-minute intra-hourly solar variability based upon hourly inputs. Short-term variability metrics can be inferred by the model using hourly insolation data from e.g., satellite-based hourly products. The trends exhibited by the models were robust and showed little site dependency (Perez et al., 2011).

Here we address the issue of intraday variability with a variability time scale of one hour. For this purpose, the daily clear sky index is used as an input to infer the standard deviation of the changes in the hourly clear sky index over the considered day.

Previous studies (Stein et al., 2012; Kang and Tam, 2013) have demonstrated that it is possible to model intra-daily variability from ground-based solar radiation daily time series.

Stein et al. (2012) introduced a new metric: the variability index, VI, to quantify irradiance variability over various timescales. Three sites were used to evaluate the consistency of this new metric. By pairing the VI index with the daily clear sky index, KT^*, they showed that a characteristic scatter plot named the "arrow-head" plot emerged from the data at hand. A classification scheme based on the VI index and clear sky index was used to distinguish between four types of irradiance days.

In a similar manner, Kang and Tam (2013) proposed a new characterization and classification method (the K-POP method) for daily sky conditions by using the daily clearness index K_D and a new metric called the daily probability of persistence (POP_D). POP_D observes differences between neighboring instantaneous clearness indices and calculates a probability that the differences are equal to zero (Kang and Tam, 2013). Three sites were chosen to test the consistency of the method. The authors showed that the annual distribution of data points in the K-POP_D plane for all three locations were enclosed by the same irregular nonagon. From the K-POP_D plane the authors also identified 10 classes that correspond to different sky conditions.

In his thesis, Dambreville (2014) proposed a classification scheme based on the daily mean clear sky index and daily variability quantified by the V metric (Coimbra et al., 2013). The classification was used to characterize the sky conditions experienced by a site located near Paris.

Some authors (Huang et al., 2014; Kang and Tam, 2015) also went further by deriving some prediction models of daily variability. For instance, Huang et al. (2014) studied the daily variability at four sites across Australia by using the Daily Variability Index (DVI) – which is similar to the VI (Stein et al., 2012). In addition to the persistence model, they also built three statistical models (including a machine learning technique) to predict the DVI using meteorological variables as predictors. The latter were selected from the global atmospheric reanalysis product of the European Centre for Medium-Range Weather Forecasts (ECMWF). However, as noted by the authors in their conclusion, the probability density function (PDF) of the DVI was not well reproduced by the statistical techniques and may suggest a limitation of these techniques in tackling the solar variability problem.

Kang and Tam (2015) used the National Weather Service (NWS) day-ahead total sky cover forecast to predict the day-ahead K_D and POP_D values. A multi-stage procedure (including a robust regression technique) was employed to estimate the parameters of a linear equation relating the daily fluctuation of solar irradiance (POP_D) to the daily fluctuation of total sky cover. The forecasting method was tested on one year of data from the Solar Radiation Research Laboratory Baseline Measurement System (SRRL BMS). As noted by the authors, overall, the proposed method provides acceptable predictions results but further improvement is needed in the intermediate K_D zone that corresponds to the lowest POP_D values (or conversely to the highest variability values).

In this study, we make a step further by analyzing intraday solar variability of twenty sites that exhibit different types of climate. For this purpose, we select 14 climatically distinct regions of North America as well as 6 subtropical/tropical island territories.

First, we propose a simple site characterization based on 2 criteria: (1) the daily clear sky index is used as an input to define a given day's meteorological conditions and (2) hourly intraday variability measured by a well-established metric – the standard deviation of the changes in the clear sky index (Perez and Hoff, 2013) – is used to quantify variability.

Second, based on a strong empirical evidence, we propose a parameterization of the intraday solar variability stating that intraday variability is a predictable function of daily clear sky index.

It must be stressed however that contrary to (Huang et al., 2014; Kang and Tam, 2015) our aim here is to propose a simple but yet effective and actionable approach.

Such a characterization would be helpful in an operational context. Predicted intraday variability enhances the informative content of day(s) ahead Numerical Weather Prediction (NWP) forecasts – operational forecasts such as ECMWF have a limited time resolution and tend to underestimate intraday dynamics. This information could be of particular relevance to grid operators' decision

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