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Dynamic Paths: Towards high frequency direct normal irradiance forecasts

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ABSTRACT

Direct normal solar irradiance (DNI) series of high-frequency time resolution permit an accurate modeling and analysis of transient processes in concentrating solar thermal power (CSTP) technologies. Numerical weather prediction (NWP) models provide an overall understanding of solar forecasting, but they are unlikely to cover a local statistical representativeness of the DNI high frequency dynamics. On the contrary, local statistical information derived from site measurements can provide statistical behavior, but may not necessarily yield an explicit model for all of the physical relationships involved. In this work, we propose a novel locally-adapted procedure for high-frequency DNI forecasting that connects these two extremes, proposing a hybrid approach in which low frequency (3-h) NWP outcomes act as boundary conditions (assuring a physical consistency with site climatic behavior) and are supplemented with Dynamic Paths of local high frequency (1-min) DNI series (assuring a statistical reproduction of site high frequency dynamics). This methodology is tested with ground measurements in 4 locations situated in different climates, and compared with a forecast base case. The analyses are carried out by classifying each measured time series into 6 categories according to its daily clearness index. Finally, metrics for adequately compare high frequency DNI forecasts are discussed.

1. Introduction

A detailed knowledge of the Direct Normal solar Irradiance (DNI) is a critical point in the design and management of a Concentrating Solar Thermal Power (CSTP) plant, since the DNI is the most determining variable in its final energy yield. High-frequency DNI series allow an accurate modeling and analysis of transient processes in some CSTP technologies, which show a nonlinear response to DNI governed by various thermal inertias owing to their complex response characteristics. DNI variability at high-frequency exerts substantial influence on the grid integration of electric power generation by CSTP technologies, which entails the necessity of developing forecasting methodologies for large-scale integration of these technologies into current energy supply structures [1,2].

Accurate DNI forecasting is of utmost importance for the optimal management of energy markets, operation of CSTP plants and for the power generation control by means of thermal energy storage (if available). This allows maintaining the grid stability in CSTP power management and ultimately facilitates the widespread implementation of CSTP technologies [3]. DNI forecasting method depends strongly on the timescale of interest, which ranges from horizons of a few seconds or minutes to several days-ahead. In the case of CSTP, the variability in irradiances is generally dampened in the electricity generation by the use of large thermal storages. Nevertheless, also CSTP plants are affected by variability of the DNI in their daily operations. For trough technologies, the second-wise or the 1-min-wise variability is not of concern, but the variability in the 10 min scale is relevant to describe transient effects [4]. On the other hand, in solar tower technologies, the high frequency on the minute scale is relevant as the thermal receiver may be damaged by

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fast and large temperature gradients. In order to avoid such gradients, the heliostats are frequently defocused and such a control system requires information on variability in and below the 1-min scale [4]. For the intra-hour and intraday, it is common to use the conversion of cloud positioning as derived by sky cameras into solar radiation deterministic models [5,6]. For 1–2 h ahead horizons, solar irradiance is predicted with good accuracy by means of statistical approaches, including ARIMA (autoregressive integrated moving averages) and ANN (artificial neural network) [1,7–11]. For 2–6 h time horizons, cloud index derived from satellite images is used in cloud-motion vector schemes [12–15]. Numerical weather prediction (NWP) schemes are also used in connection to air quality models to provide forecasts taking aerosol variability into account [16–19]. Forecast models for the 1–5 days ahead have also been developed with good accuracy and reliability [1,20]. It is worth to highlight that the vast majority of conventional generation is scheduled in the day-ahead market [21].

Unfortunately, the solar irradiance forecast in NWP models has not been treated traditionally as a priority as it has been mainly used to force the average Earth's surface energy balance. This situation, influenced by the traditional lack of major stakeholders, is changing in recent years in which substantial investments are now being made in this field due to the increasing demand for operational and improved solar forecasts. In this regard, it is worth to mention verification efforts that have recently been undertaken with respect to hourly resolved DNI forecasts as provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [22]. Notwithstanding, it is clear that the industry demands higher temporal resolution forecasted DNI series that those achieved by NWP models, which typically ranges from 1 h to 3 h in global scale modeling. Also, a detailed site dynamic of high-frequency DNI is not provided by these models [23]. The high variability of atmospheric phenomena as clouds and aerosols, the complex atmospheric modeling on which NWP models rely, the extremely large underlying systems for data capture and assimilation and, in general, the large uncertainty associated with weather behavior makes accurate localized and high-frequency forecasting a very difficult task.

The variability of solar irradiance is strongly dependent on the local microclimate and the averaging timescale used [24–26]. Apart from the solar position (which is completely deterministic), the DNI variability is mostly due to clouds, which can be associated with a stochastic nature as precise models for cloud dynamics have proven elusive [27]. Aerosols also contribute to the DNI variability, but they cause variations on a several-hour time scale [28] while clouds affect DNI in the minute time scale: CSTP plants production changes can exceed 50% of the clear sky generation potential over two to 5 min [29]. Moreover, rapid changes in solar power output can impact markets with sub-hour intervals, reserve requirements, net load variability, regulation requirements, and the operation of other generators [30]. To capture these potentially challenging events in technology evaluation studies, high temporal resolution input DNI data are required.

In this work, we present a novel approach for statistical post-processing of 3-h DNI series that dynamically assembles site information to provide high frequency DNI series up to the temporal resolution of available measurements at the site. The 3-h temporal resolution is selected as a case study based on the ECMWF, which provides both global and direct irradiance forecasts commercially at this time resolution. The rationale for this data-driven approach is that patterns exist in the historical dataset that can be used for characterizing high frequency DNI dynamics at the site [31] together with a forecast of the DNI values at clearest sky conditions. This novel approach is compared with a base case, consisting in the linear interpolation of clear sky condition each 3-h throughout the day.

The paper is presented as follows: Section 2 describes measured data used in the work, as well as the analysis carried out. Section 3 shows the results found and in Section 4 discussion, conclusions and future work are drawn.

2. Methods

2.1. Ground-measured observations

For this study, we have selected high quality solar irradiance data from the Baseline Surface Radiation Network (BSRN) stations [32] located at Carpentras (CAR), Lauder (LAU), Sede Boquer (SBO), and Tamanrasset (TAM). Table 1 shows details about the locations of the stations selected for this study, as well as their climatic conditions according to the Köppen–Geiger classification [33]. This climatic scheme divides the climate in five main types and several subtypes, mainly based on mean temperature and precipitation values. A further characterization of the stations CAR, SBO, and TAM is provided by making use of variability classes as suggested by Ref. [34]. Fig. 1 provides frequency histograms of the occurrence of each variability class in the time series from 2005 to 2011 in CAR and SBO (left), and from 2008 to 2014 in TAM (right). LAU location is excluded from this analysis because the classification scheme has been developed and tested also with satellite data, and is therefore available only for the Meteosat Second Generation field of view.

The most frequent case in CAR location is the variability class 8

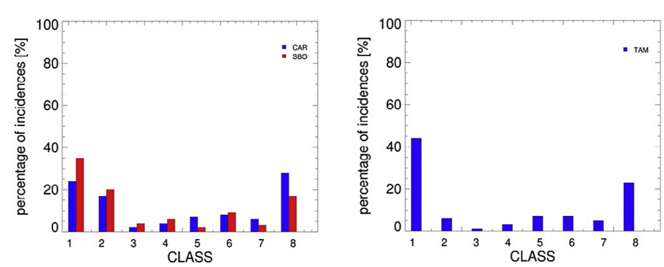

Fig. 1. Frequency histogram of variability classification results for BSRN stations CAR, SBO, and TAM based on daytime hours in the years 2005–2011 (for CAR and SBO, left) and 2008–2014 (in the case of TAM, right).

Table 1
Radiometric stations selected for this study.

Location (ID)	Country	Coordinates	Altitude (m)	years	Climate following Köppen and Geiger
Carpentras (CAR)	France	44.0830 N 5.0590 E	100	2005–2011	Mediterranean
Sede Boquer (SBO)	Israel	30.8597 N 34.7794 E	500	2005–2011	Hot desert, arid
Tamanrasset (TAM)	Algeria	22.7903 N 5.5292 E	1385	2008–2014	Hot desert, arid
Lauder (LAU)	New Zealand	45.0450 S 169.6890 E	350	2008–2014	Oceanic