INCREASING THE TEMPORAL RESOLUTION OF DIRECT NORMAL SOLAR IRRADIANCE DATA USING THE SOUTH AFRICAN UNIVERSITIES RADIOMETRIC NETWORK

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Abstract

High resolution direct normal irradiance (DNI) data is required in order to accurately model the electrical yield of a concentrating solar power plant. In most cases the irradiance data from historical and typical meteorological year sources are hour averaged. This paper demonstrates the use of a method proposed by Fernandez-Peruchena et al. in combination with high temporal resolution DNI data from the Southern African Universities Radiometric Network. The method is shown to successfully generate minute resolution data from hour averaged data from two measurement stations in South Africa.

Keywords: Direct normal irradiance; synthesis of solar irradiance data; high temporal resolution data; CSP yield analysis

1. Introduction

Most of the available irradiance data from historical and satellite derived sources are hour averaged. In order to accurately calculate the yield of a concentrating solar power (CSP) plant, it is essential to account for high-resolution temporal variability of the site data [1].

The reason that hourly averaged DNI data is not acceptable for accurate yield analysis of a CSP plant is because hourly measurements are too infrequent to capture the transient effects of clouds [2]. The transient nature of DNI causes a nonlinear response of a CSP plant [3].

Fortunately there is a free source of minute averaged DNI data in Southern Africa. The Southern African Universities Radiometric Network (SAURAN) is a regional network of sixteen solar monitoring stations. The data is accessible to the public via a website interface. Each of the stations measure direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), global horizontal irradiance (GHI) as well as other meteorological data. The data is available in time-averaged formats over 1-minute, hourly and daily intervals.

The aim of SAURAN is to provide a long-term record of solar resource in Southern Africa, a region that shows high potential for the implementation of various solar energy technologies [4].

2. Motivation

When planning a CSP plant, accurate yield analysis is a key issue throughout all phases of project development and it concerns many of the stakeholders [5].

The two primary CSP technologies currently being implemented are parabolic troughs and central receivers. The effect of using minute averaged data as opposed to hour averaged data has been investigated when modeling a parabolic trough plant [3]. It was found that using hourly data resulted in an overestimation of daily electrical energy yield of between 10 % and 20 %.

In order to further illustrate the need for high resolution data, the influence of DNI temporal resolution on the electrical yield of a central receiver model has been investigated. An existing central receiver model was used together with minute and hour averaged solar data. Data from the SAURAN station at the University of the Free State (UFS) was used for the comparison.

The model is built in the MATLAB® Simulink environment in order to simulate the operation of a 100 MW_e (gross) molten salt central receiver plant. The receiver performance is taken from the thermal resistance receiver model designed by de Meyer et al. [6] for a proposed plant in South Africa. The thermal energy storage system is sized to store enough energy to allow for design point electrical generation for 12 hours.

The model uses DNI, ambient temperature and wind data to calculate electrical yield output for a proposed site. It consists of different component blocks which replicate the performance of major components within a central receiver CSP plant (Figure 1).

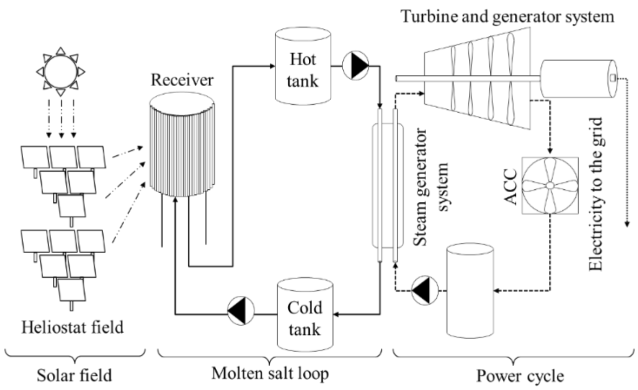

Fig. 1. Simplified schematic diagram of a molten salt central receiver system

The model uses heat transfer fluid (HTF) mass flow, enthalpy and temperature to perform energy balance calculations at each system component.

A cloudy summer day in December 2014 was used to illustrate the difference in electrical yield of the model using minute and hour averaged DNI data (Figure 2). Hourly temperature and wind data was used for both simulations.

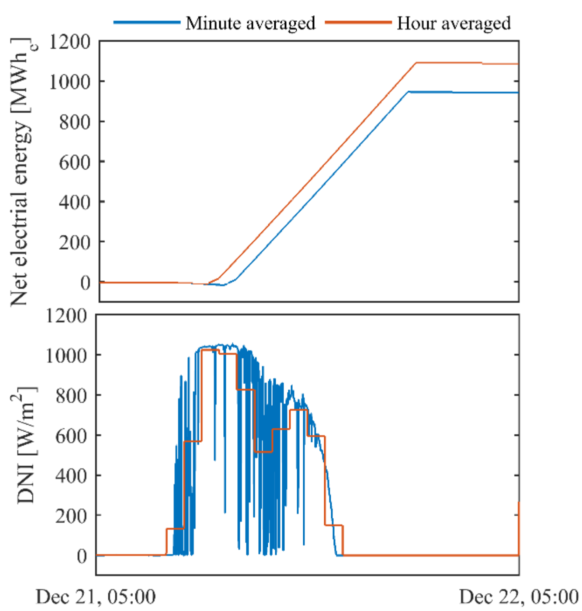

Fig. 2. The effect of hour vs minute averaged DNI data on the performance of a central receiver model over one day of operation

The model calculated a daily electrical yield of 1087.1 MWh$_e$ using the hour averaged DNI data. Using the minute averaged DNI data, the model calculated a daily yield of 941.9 MWh$_e$.

The 15.4 % overestimation in electrical yield using the hour averaged data is caused by a nonlinear response of the plant to DNI. This is governed by the thermal inertia of the receiver and the part-load performance of the steam cycle.

The overestimation of electrical yield of a central receiver plant and a parabolic trough plant when using hour averaged data demonstrates the need for higher resolution DNI data.

3. Methodology

The method developed by Fernandez-Peruchena et al. [7] was used to increase the temporal resolution of DNI data. The method was implemented using data from the SAURAN network.

3.1. Measured data

The DNI datasets used in this investigation were taken from SAURAN stations at the University of the Free State (UFS) in Bloemfontein and Graaff-Reinet (GRT) in the Eastern Cape (Table 1).

Station	Lat. [°]	Long. [°]	Elev. [m]
UFS	-29.110	26.185	1491
GRT	-32.485	24.585	660

Table 1. SAURAN station locations

The datasets were collected by Kipp & Zonen CH1 Pyrheliometers mounted onto Solsys solar trackers. Both stations were calibrated in the second half of 2013. Minute averaged DNI datasets were used from both stations for the 2014 and 2015 years. Hour averaged datasets were also used for the 2014 year. A simple quality control procedure was used to detect any missing data points or irregularities in measurement.

3.2. Generation of high resolution data

The method proposed by Fernandez-Peruchena et al. [7] uses a technique for the nondimensionalization of a series of ground measured, high frequency daily DNI curves. The process of nondimensionalization transforms each measured day into a dimensionless signature that can be used to create high resolution DNI data from hourly DNI data.

The 2015 data set for each of the sites was used for the nondimensionalization process. The first step of this process is to calculate a clear sky envelope for each of the 365 measured days. Curve fit parameters are used to adjust the envelope curve to accurately fit the DNI curve of each given day.

The fitted envelope is then used to generate a dimensionless DNI curve for each day. At each time step the measured DNI value is divided by the value of the envelope curve. In order to nondimensionalize the time scale the elapsed solar time starting at sunrise is divided by the day length for each individual day. The result of the nondimensionalization is a high resolution DNI signature for the day that has a time scale and a DNI scale ranging from 0 to 1.

The 2014 hour averaged data set was used for the following step. For each day of the hour averaged data range, a clear sky envelope is fit to the DNI curve. Each of the high resolution signatures is then applied to the clear sky envelope. This results in an estimated minute resolution DNI curve for the day.

An algorithm is then used to search for the most appropriate signature to fit the given DNI curve in terms of the Euclidean distance between hourly values of the measured and generated DNI series. The best fit signature is selected for each of the days, which results in a full year of synthetically generated DNI data.

3.3. Evaluation of generated high resolution data

The measured minute averaged values for the 2014 datasets were used to evaluate the accuracy of the generated minute averaged data set.

Statistical indicators were used in order to determine how accurately the generated data matches the measured data on an annual basis. A review of the statistical indicators for modeled solar radiation [8] was used as a basis for the evaluation of the generated (or predicted) and measured data.

For the purpose of statistical evaluation, the measured DNI values are referred to as the observed values and the generated DNI values are referred to as the predicted values.

Indicators of dispersion were used to compare the predicted DNI data points (p_i) to the observed data points (o_i). The two indicators of dispersion used were the normalized root mean square deviation (NRMSD) and the mean bias deviation (MBD).

$$MDB = \frac{\frac{1}{N}\sum_{i=1}^{N}(p_i - o_i)}{O_m}$$

$$NRMSD = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(p_i - o_i)^2}}{o_{max} - o_{min}}$$

Where o_{max} and o_{min} represent the maximum and minimum DNI values of the observed range and O_m represents the average of the observed range. The number of data points in the set is denoted as N. Values tending towards zero for the indices of dispersion represent a significant correlation between the predicted and observed datasets.

In order to get an indication of the overall statistical performance of the method used, the Nash-Sutcliffe efficiency (NSE), the Willmott index of agreement (WIA) and the Legates coefficient of efficiency (LCE) were used.

$$NSE = 1 - \frac{\sum_{i=1}^{N}(p_i - o_i)^2}{\sum_{i=1}^{N}(o_i - O_m)^2}$$

$$WIA = 1 - \frac{\sum_{i=1}^{N}(p_i - o_i)^2}{\sum_{i=1}^{N}(|p_i - O_m| + |o_i - O_m|)^2}$$

$$LCE = 1 - \frac{\sum_{i=1}^{N}|p_i - o_i|^2}{\sum_{i=1}^{N}|o_i - O_m|^2}$$

The overall performance methods indicate 1 for perfect agreement and either $-\infty$ (NSE and WIA) or 0 (LCE) for complete disagreement.

In order to calculate the similarity between the generated and measured DNI data, the Kolmogorov-Smirnov test Integral (KSI) index was used. The KSI calculates the integrated difference between the cumulative distribution functions (CDF) of the two data sets [9]. The process for calculating the KSI is shown graphically in the results section (Figure 4).

$$KSI = \frac{100}{A_c}\int_{xmin}^{xmax} D_n \, dx$$

Where D_n is the absolute difference between the two normalized CDF distributions within irradiance interval of the measured and generated data sets. The critical area (A_c) is calculated as a function of the maximum(x_{max}) and minimum(x_{min}) DNI values, and the number of points used in the CDF distribution (N):

$$A_c = \frac{1.63}{\sqrt{N}} \cdot (x_{max} - x_{min})$$

The KSI approaches zero as the two CDF distributions become identical. The two datasets can then be significantly similar in a statistical sense.

4. Results

In order to evaluate the performance of the method when using SAURAN data, the generated data is compared to the measured data for three different days at different sites. Statistical indicators (Section 3.3) were then used to evaluate the accuracy of the method in terms of the annual performance.

4.1. Comparing daily measured and predicted DNI data

The generated DNI curves are compared to the measured DNI curves in Figure 3. The figure shows three different days of data for both the UFS and the GRT sites.

The first column shows a clear day with no cloud cover. The method generates a very similar DNI curve to the measured DNI curve for both sites when there are no cloud transients influencing the available solar resource.

The second column shows days with scattered clouds during an extended portion of the day. At the UFS site, the model appears to accurately generate the DNI curve of a day with clear skies

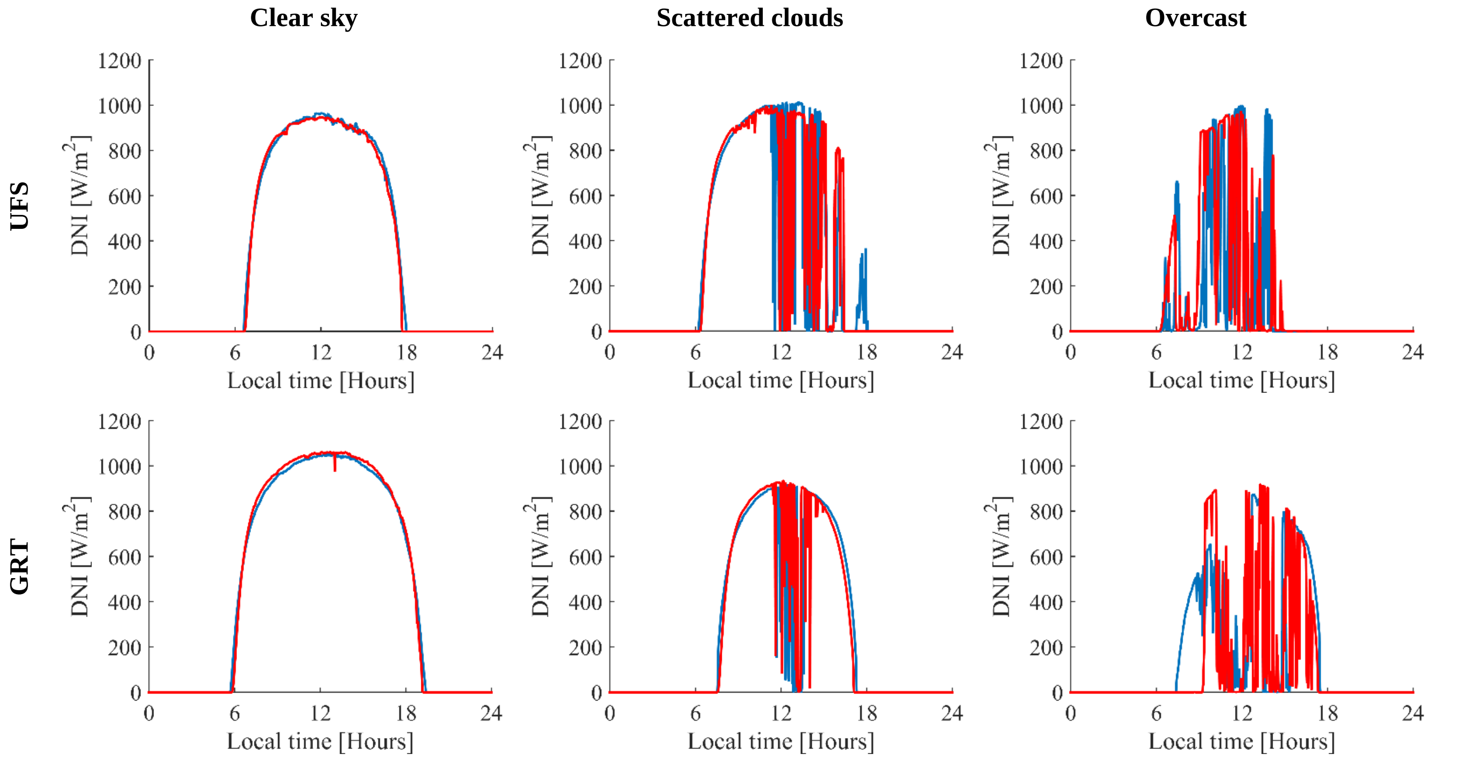

Fig. 3. Comparison of synthetically generated (red) and measured (blue) DNI curves

in the morning and scattered clouds in the afternoon. This DNI pattern is typical in Bloemfontein.

It must be noted that the method does not precisely predict individual data points. However, it successfully predicts characteristic fluctuations in DNI at the correct periods in the day while ensuring that the total available solar energy remains constant.

The third column compares the performance during days with frequent clouds and low DNI. At the UFS site the generated data matches the measured data.

The GRT cloudy day example shows the limitation of the method. The generated DNI curve does not match the measured curve in the morning; it then overcompensates with a peak as the time approaches noon. The accuracy could be improved using a larger high resolution data set which would lead to improved characterization of the DNI curves and a more accurate matching of generated and measured data.

4.2. Evaluating the statistical performance of the method

This section evaluates the performance of the method in generating a full year (2014) of high resolution DNI data from hour averaged data for the two selected locations. The evaluation is performed by comparing the observed minute averaged data to the generated minute average data.

Indicators of dispersion were calculated for the GRT and UFS datasets (Table 2). The percentage values calculated for the MBD and NRMSD are low, which indicate low dispersion and a good performance of the method.

Parameter	GRT	UFS
MBD [%]	0.28	0.43
NRMSD [%]	10.40	9.74

Table 2. Annual indicators of dispersion

Overall statistical performance indicators were calculated for the GRT and UFS datasets (Table 3). The NSE, WIA and LCE are all above 0.8, where a value of 1 indicates a perfect match between the data being compared. This is considered an acceptable indication that the method has performed well at both locations.

Parameter	GRT	UFS
NSE	0.8217	0.8478
WIA	0.8221	0.8481
LCE	0.8120	0.8432

Table 3. Annual overall statistical performance indicators

The procedure for calculating the KSI for the UFS and GRT datasets is illustrated in Figure 4. The first column shows the observed and the predicted normalized frequency of the DNI datasets.

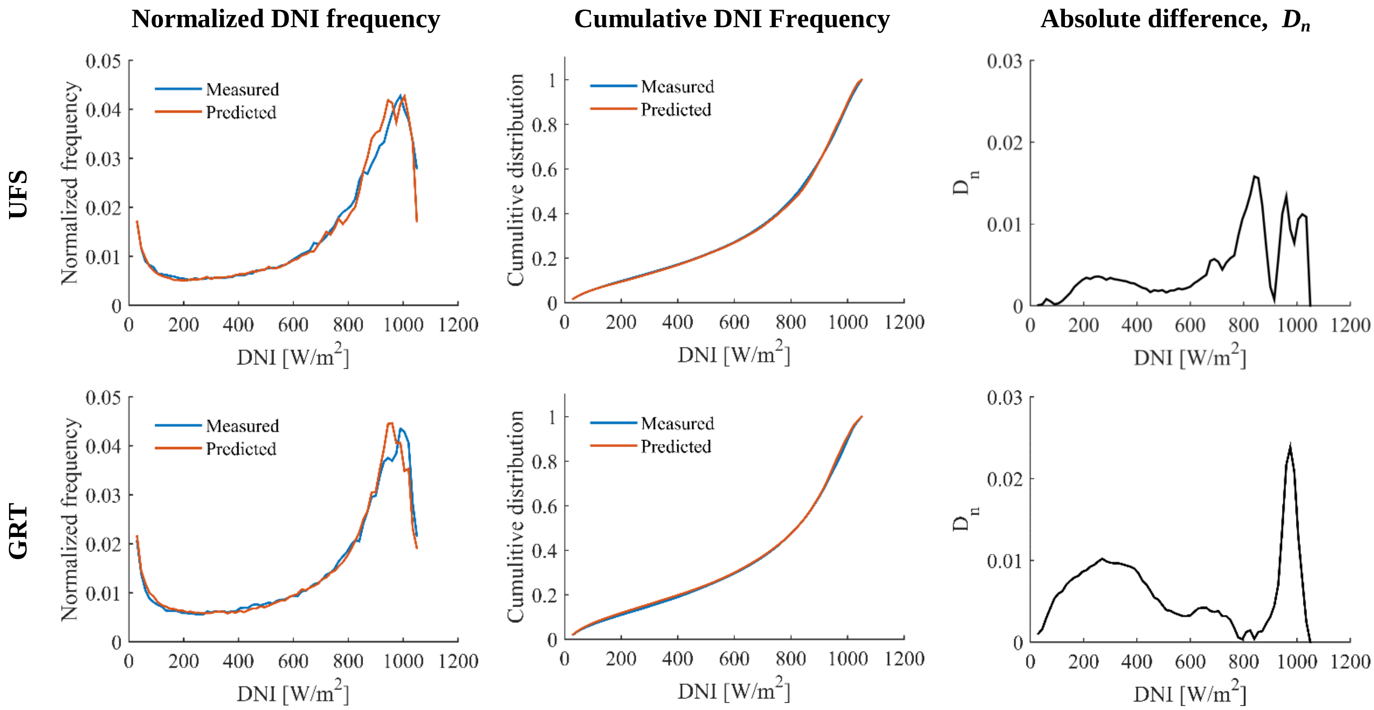

Fig. 4. KSI calculation procedure: normalized frequency, cumulative distribution and absolute difference plots for two stations

The second column shows the CDF for the observed and predicted datasets at both sites. The third column shows the absolute difference (D_n) between the predicted and the observed CDF curves.

The KSI index is calculated as 3.13 % for GRT and 2.34 % for UFS. The KSI indices suggest that the statistical distribution of the predicted and measured DNI data over the year is almost identical for both of the sites.

Considering the indicators of dispersion, the indicators of overall statistical performance and the KSI indices, the method generates DNI data for both of the sites with a significant correlation to the measured data.

5. Conclusion

High resolution DNI data is required in order to accurately model the electrical yield of both parabolic trough and central receiver CSP plants.

A method developed by Fernandez-Peruchena et al. was implemented using DNI data acquired from the SAURAN network. Synthetic minute averaged DNI datasets were successfully generated using given hourly DNI datasets.

The statistical comparison of the generated and measured DNI datasets indicates no significant difference at either of the locations. This shows that the method for generating synthetic DNI has performed well.

While the annual solar energy is correctly generated using the method, individual days of the generated DNI do not exactly match the measured DNI. This could result in minor errors while modeling the electrical yield of a CSP plant. Further investigation is required to determine the effect of these deviations on a daily basis.

In future work this method will be applied to hour averaged satellite data of locations near to the SAURAN measurement stations in order to generate high resolution DNI data. This data will be used for electrical yield analysis of both parabolic trough and central receiver CSP plants.

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