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Generation of series of high frequency DNI years consistent with annual and monthly long-term averages using measured DNI data

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Abstract

In recent years, many researchers are suggesting that statistical approaches are needed to achieve sound estimates of the economic feasibility of commercial Concentrating Solar Thermal Power (CSTP) plants. A key element of such statistical approaches is the capacity of generating large series of high-frequency years which are consistent with the estimated variability of the monthly and annual values of the relevant meteorological variables.
This paper presents a method of using high-frequency solar Direct Normal Irradiance (DNI) measurements to generate high frequency DNI series consistent with the variability and distribution of natural series, and also matching monthly and annual long term averages. The method takes advantage of a novel technique for the nondimensionalization of measured high-frequency daily DNI curves. This nondimensionalization technique makes it possible to consistently use measured solar DNI data to generate new daily curves of high-frequency DNI data and the subsequent long series of high-frequency DNI years. The novel technique for the nondimensionalization of measured high-frequency daily DNI curves is based on the nondimensionalization of the temporal scale by dividing the elapsed Universal Time (UT) since sunrise by the total elapsed UT from sunrise to sunset and on the nondimensionalization of the solar DNI scale by dividing each actual solar DNI value by the corresponding DNI value of the clear-day solar DNI envelope curve.

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Keywords: DNI, high frequency; synthetic generation; enveloping; nondimensionalization; CSP, TMY

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1. Introduction

When analysing the economic feasibility of a commercial Concentrating Solar Thermal Power (CSTP) plant, the usual approach consist in developing an energy model of the CSTP plant and in feeding this model with a Typical Meteorological Year (TMY), which specify the instantaneous values of solar Direct Normal Irradiance (DNI) and other relevant meteorological variables at high frequency (i.e., time intervals of 10-minutes or less), in order to obtain an estimate of the annual average energy production of the CSTP plant. This annual energy production of the plant is then used, together with an estimate of the investment cost of the plant and its yearly operating and maintenance costs to compute the Internal Rate of Return, the Levelized Cost of Energy, and other economic indicators that are of interest for the economic feasibility analysis.

Strictly speaking, the construction of a TMY requires of the order of 30 years of high-frequency measured DNI and other relevant meteorological data [1]. Since such long term high frequency series of measured DNI and other meteorological data are seldom available for most locations on Earth, satellite-derived series and Numerical Weather Prediction Models (NWPM) are usually employed instead. These methods are capable of estimating the long-term average of the annual and monthly Direct Normal Insolation and of other relevant meteorological variables; however they do not provide the high frequency instantaneous value data required to simulate the energy behaviour of the CSTP plant.

To generate a high-frequency year of meteorological data, consistent with the long-term annual and monthly estimates, several approaches have been proposed in the literature. These approaches are, at best, useful to generate one high-frequency pseudo-TMY, which could then be used in conjunction with the energy model of the plant to estimate the annual long-term average electricity energy production. For economic feasibility studies and financial projections of debt servicing the TMY approach has been questioned as an appropriate methodology on the basis that it intentionally rules out the possibility of “extreme” years, and, therefore, consistently underestimates the risk of “bad meteorological years” and the effect of the associated poor annual electricity production [2].

In recent years, CENER, Sandia National Labs, and other research organizations are advancing the idea that more sophisticated approaches are needed to estimate the economic feasibility of a commercial CSTP plant project, which address both the variability of the solar resource and of the cost of some key investment and operation and maintenance elements of the plant as well as the uncertainty associated with the energy model estimates and cost data. In particular, there is an increasing interest in adopting probabilistic approaches to model variability and uncertainties in both electricity production and system cost to achieve sound estimates of the economic feasibility of commercial Concentrating Solar Thermal Power (CSTP) plants [3, 4].

A key element of such more sophisticated approaches to the feasibility analysis of a CSTP plant is the capacity of generating no one high-frequency TMY year, but a large series of high-frequency years, which are consistent with the estimated variability of the monthly and annual values of solar radiation and of other relevant meteorological variables. An efficient and robust general scheme for the generation of such large series of high-frequency synthetic TMYs does not exist yet. Many complex issues have to be addressed to develop such scheme. This article addresses one of those issues: the generation of synthetic typical high-frequency solar DNI years from typical daily solar DNI years and one-year of high-frequency solar DNI measurements.

2. Current methodologies for the generation of high-frequency direct solar radiation years

Modeling system performance and economics of solar thermal power plants has been carried out traditionally by means of deterministic analyses. Most CSTP energy simulation tools use a Typical Meteorological Year (TMY) as one of their main input to assess to assess the annual energy production of a CSTP plant [1, 5]. In broad terms, a TMY can be defined as a series of hourly values of the relevant meteorological variables, measured or estimated, at the plant location. Usually, these hourly values are considered “specific (point) values” rather than distributions of values that reflect the inherent uncertainty in many of the CSTP plant features and processes. As a result, the confidence and uncertainty associated with the results are unknown [6].

Current TMY approach to solar resource assessment is based on a two-step procedure: (1) an estimation of the long term annual and monthly direct solar insolation of accumulated values, and (2) the selection of concrete days of measured direct solar irradiance data to reproduce the long term annual and monthly solar insolation accumulated behavior. For estimating the long term values of solar radiation, two main methodologies are used: the weighted mean of different databases [7, 8], and the use of long series of solar irradiance insolation data estimated by satellite, or from Numerical Weather Prediction Models.

The needed measured data to build the high-frequency TMY is obtained from the measurement campaign carried out at the plant location. For commercial CSTP plants, the measurement campaign consist usually of one year of solar DNI and other relevant meteorological measurements taken on site at hourly or lower time intervals. Obviously, in almost all cases, the monthly and annual direct solar insolation values of the measured year do not fully agree with the corresponding long-term direct solar insolation estimates. Because of that, the measured year cannot be used as the high-frequency TMY for the site. But, the TMY for the site can be constructed from the measured year by replacing days of the measured years with other days of the same year in order to change the annual and monthly direct solar insolation of the year so that they agree with the corresponding long-term estimates.

Obviously, because the duration of the days varies with the date, the available options to replace a day by another are rather limited: Only days which are close to each other in the year, i.e. days which have relatively similar daylight duration can be interchanged. This limitation precludes the use of this approach to generate long series of direct solar radiation year which are compatible with the long-term estimates of the annual and monthly direct solar insolation values and their statistics. This is the main reason this methodology is used to generate just a representative TMY for the location under consideration.

3. New methodology based on the nondimensionalization of the DNI daily solar radiation curve

To overcome the limitation of the traditional approach to generate high-frequency direct solar radiation years using the solar radiation data obtained in the one-year measurement campaign, a new strategy is proposed in this article. This strategy is centered on the use of nondimensionalized high-frequency measured daily DNI curves as the basic building element of high-frequency DNI months and years compatible with the long term solar radiation behavior expected at a given site. The daily DNI curve is the representation of DNI data against Universal Time (UT). To fully nondimensionalize this curve it is necessary to non-dimensional time as well as DNI data. This can be done by defining characteristic values of time and DNI and divide the elements of each duple (time, DNI) by the corresponding characteristic values.

For a given daily curve of high-frequency DNI data, the nondimensionalization of time is achieved by counting time from sunrise and dividing the elapsed time since sunrise by the total time elapsed between sunrise and sunset for that given day. Likewise, the nondimensionalization of a DNI datum is achieved by dividing this datum by the corresponding value of the clear-day solar DNI envelope. As shown in Fig. 1, this nondimensionalization scheme transform every daily high-frequency DNI curve into a dimensionless curve where the dimensionless time scale goes from 0 to 1 and the dimensionless DNI scale goes also from 0 to 1.

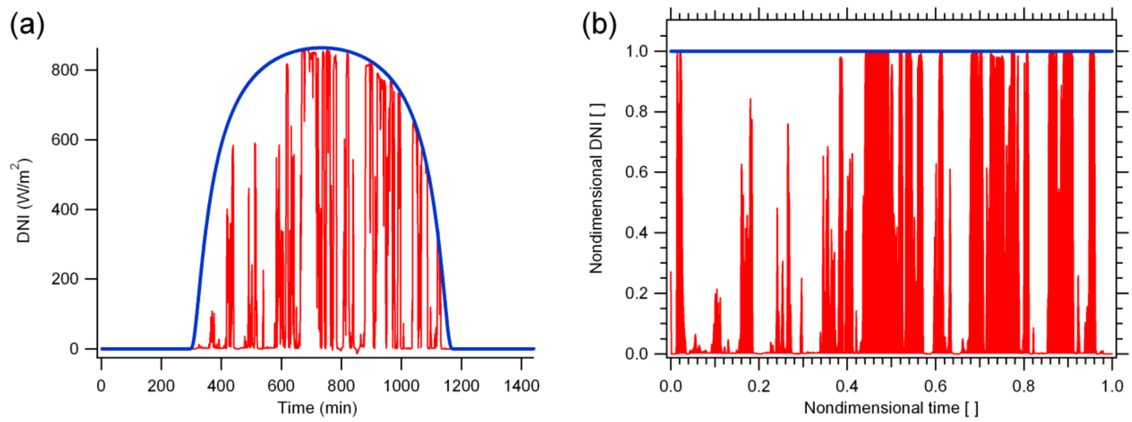

Fig. 1. (a) Instantaneous DNI daily curve and its clear-sky envelope; (b) nondimensionalized DNI curve.

The clear-day solar DNI envelope is calculated by appropriately adjusting the two parameters (E_0, β) of the clear-day ASHRAE exponential decrease model [11] so that the curve defined by the model is the tightest possible upper boundary of the cloudless measured DNI values for the given day. The ASHRAE exponential decrease model is defined by the following expression:

$$DNI = E_0 \cdot \exp\left(\frac{-\beta}{\sin(\phi)}\right) \tag{1}$$

Where: DNI is the solar direct normal irradiance, ϕ the solar elevation, E_0 the apparent extra-terrestrial irradiance, and β the overall extinction parameter.

To adjust the parameters (E_0, β) in order to obtain the clear-day envelope of every measured high-frequency daily DNI curve a slightly modified version of the algorithm proposed for that purpose by Gómez-Camancho and Blanco [12] is used. The proposed full nondimensionalization of the daily solar DNI curve has several interesting properties. For the purpose at hand, the following are of special interest:

- All daily solar DNI curves are mapped into the unit square.
- Ideal clear-days DNI curves (those which follow the clear-day DNI envelope) are mapped into upper horizontal border of the unit square.
- The area under the mapped dimensionless DIN curve in the unit square is a number between 0 and 1, which equals the ratio between the actual dialy direct solar insolation and the maximum daily direct solar insolation corresponding to the ideal clear-day DNI curve.

Since once they are transformed, all dimensionless daily DNI curves in a year have the same horizontal and vertical scales, any day may be replaced by any other day. Regarding time, there are 365 distinct different possibilities, since the duration of each day along the year is fixed for a given location. However, regarding the selection of clear-day envelopes the possibilities are countless, since for every day of the year the values of the tuple (E_0, β) are not deterministically fixed. This makes it possible to use just a year of high-frequency DNI data to generate a very large number of high-frequency DNI years which are consistent with the long-term monthly and annual DNI estimates and their associated statistics, and which capture the high-frequency behaviour of the DNI at the specific site.

As stated in the introduction, an important step towards defining an efficient and robust general scheme for the generation of large series of high-frequency synthetic TMY is the generation of synthetic typical high-frequency solar DNI years from series of typical daily solar DNI years and one-year of high-frequency solar DNI measurements.

In this article we are not addressing the issue of how to generate the series of typical daily solar DNI years (this a research topic in itself), but we are proposing a methodology that will allow the transformation of those series of typical daily solar DNI years into series of high-frequency solar DNI years (10-minutes or less), which can be used to feed CSTP energy models in order to get an estimate of the long-term average annual energy production of the CSTP plant at a given site and its associated probability distribution.

This methodology consist in selecting, for each one of the 365 daily direct solar radiation insolation values that compose a given typical daily solar DNI year, the nondimensionalized high-frequency daily solar DNI curve which once transformed back into a dimensional high-frequency daily curve has a direct solar daily insolation closest to the solar radiation insolation value of the given day.

4. Testing the validity of the new proposed methodology for generating high-frequency typical DNI years

To test the validity of the new proposed methodology for generating high-frequency typical DNI years from series of typical daily solar DNI years and one-year of high-frequency solar DNI measurements, the following steps were carried out:

1. Several typical daily years of solar DNI for a given location were obtained,
2. One year of high-frequency solar DNI measurements for that same location was also obtained.

3. The methodology presented in the previous section, based on the use of nondimensionalized high-frequency daily curves, was used to generate the corresponding synthetic high-frequency solar DNI years.
4. A statistical test was carried out to proof that the high-frequency solar DNI years generated are indeed typical of the given location, i.e., that these synthetic years cannot be statistically distinguished from real high-frequency years measured at the given location.

We used solar radiation measurements from the Baseline Surface Radiation Network (BSRN) station of Carpentras (France). The BSRN is a project of the World Climate Research Program (WCRP) that aims to measure radiative fluxes at the Earth surface with the highest possible accuracy using meteorological stations with well-calibrated state-of-the-art instrumentation at selected sites in the major climate zones [9]. At the Carpentras BSRN station, as in most BSRN stations around the world, DNI is measured with a Pyrheliometer, Kipp & Zonen, CH1, and it is sampled at 1 Hz with a one-minute averaging time. BSRN data undergo rigorous quality checks [9, 10], to assure high accuracy as well as homogeneity in the data.

The measurement periods used to generate the series of typical daily years (step 1) and to test the validity of the methodology presented in the previous section (step 4) correspond to fourteen consecutive years, from 1998 to 2011, which include a wide range of conditions representative of the location, including composition of cloud types, the occurrence of differential aerosol loading and ranges of atmospheric humidity, and different seasonal conditions among others. The year used as one year of high-frequency solar DNI measurements for the location (step 2) was 1997.

The statistical metric used to check that the high-frequency solar DNI years generated are indeed typical of the given location (step 4) is the KSI (Kolmogorov–Smirnov test Integral) index, which is the integral of the differences between the Cumulative Distribution Functions (CDF) of two data sets [13]. The KSI is therefore calculated as follows:

$$KSI = \int_{x\min}^{x\max} D_n dx \tag{2}$$

In practical terms, as D_n is a discrete variable and the number of integration intervals is identical in all cases, trapezoidal integration is used over the whole range of the independent variable x. A relative value of KSI is obtained by normalizing the critical area, $a_{critical.}$

$$KSI(\%) = 100 \frac{\int_{x\min}^{xman} D_n dx}{a_{critical}} \tag{3}$$

where $a_{critical}$ is calculated as:

$$a_{critical} = V_c \cdot \left(x_{\max} - x_{\min} \right) \tag{4}$$

And V_c can be determined from the number of values N in the sample:

$$V_c = \frac{1.63}{\sqrt{N}}, N \geq 35 \tag{5}$$

The minimum value of the KSI(%) index is zero, which means that the CDFs of the two sets compared are equal. Since KSI(%) is below 100% when frequency distributions are close to each other [7], for our purposes any value of

KSI(%) below 100 is considered to be a proof that the synthetic years cannot be statistically distinguished from the real high-frequency years measured at the location.

5. Results

Fig. 2 shows the frequency histograms of the fifteen years of high-frequency (1-minute) solar DNI data measured at the Carpentras BSRN station used to validate the methodology for generating high-frequency typical DNI years presented in this article. It is clear from the figure that the all histograms exhibit a very similar pattern, having their peaks and valleys located at approximately the same range of DNI values. In the figure the year 1997, which was used in the validation process as the one year of high-frequency solar DNI measurements used to extract the nondimensionalized solar DNI curves is plotted in red in Fig. 2.

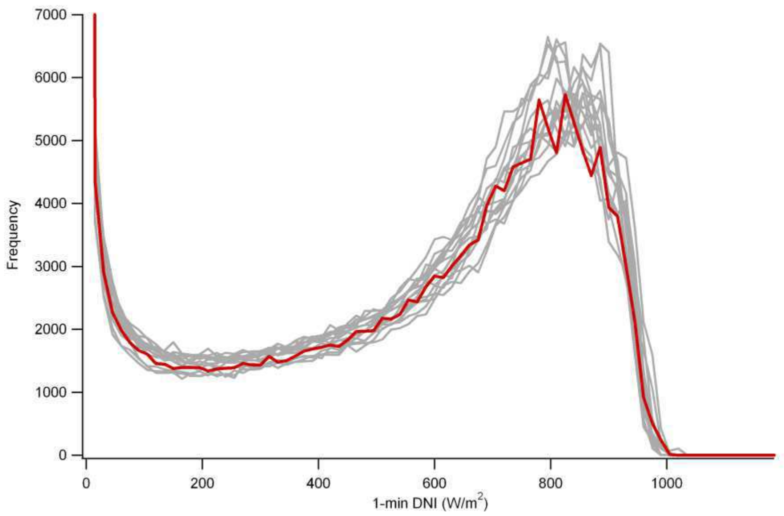

Fig. 2. Frequency histograms of 1-min DNI series measured at carpentras BSRN station (1997-2011). Frequency histogram corresponding to 1997 is plotted in red.

As a result of the generation method proposed, we obtain 1-min DNI series reproducing daily DNI values imposed as input. The 1-min DNI generated series does not intend to be coincident with the measured ones, but account for its variability and distribution. This is clearly shown in Fig. 3 (a), where 3 days of measured and generated DNI values are represented. The first day series are very similar, with the exception of a passing cloud. In the second day shown in Fig. 3 (a) both series follow a similar tendency, showing also similar maximum values and variability, although they are less coincident than the ones of the first day. In the third day shown in Fig. 3 (a), on the other hand, it can be appreciated a contrary tendency between both datasets: while measured series are near zero approximately until the solar noon, the generated series follow the opposite pattern, decaying at zero after the solar noon. Notwithstanding, both series show similar values and present the similar variability, which is the goal the new methodology aims to achieve. The similitude of both datasets distributions, 1-min measured and generated DNI, can be appreciated in frequency histograms of the whole period compared (from 1998 to 2011), Fig. 3 (b).

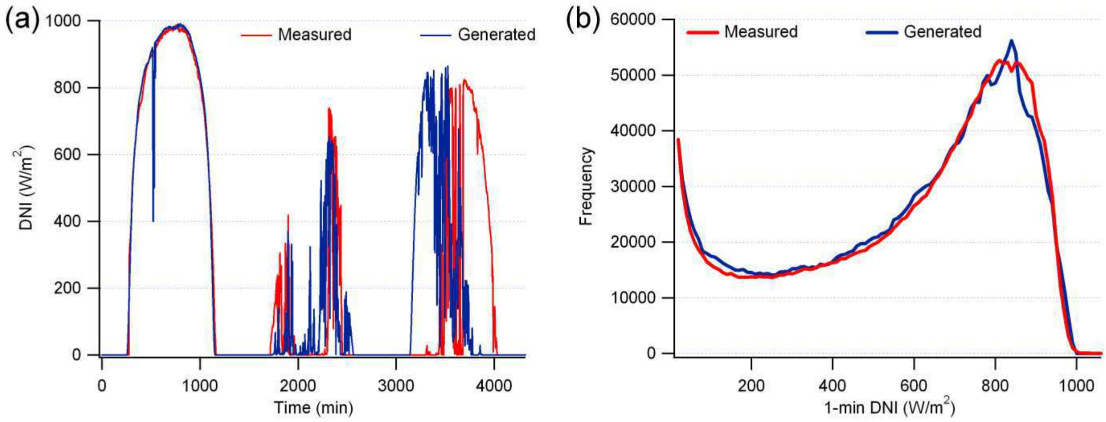

Fig. 3. (a) 1-min DNI series measured and generated; (b) frequency histogram of 1-min DNI measured and generated for 1998-2011.

Fig. 4 shows graphically the KSI% values for measured versus generated 1-min DNI series for each of the fourteen years analyzed, as well as for the whole fourteen years period considered as a whole. As was stated in the previous section, as long as the KSI% index is below 100, it can be stated that the series being compared are statistically identical. As the figure shows, in all cases, the KSI% index is well below that threshold, which proofs that the high-frequency (1-minute) synthetic years produced using the proposed methodology cannot be statistically distinguished from real high-frequency years measured at the location.

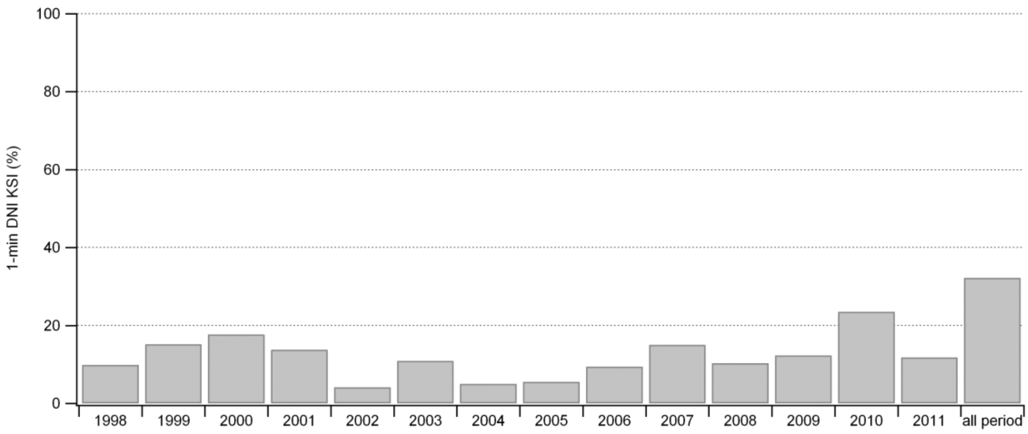

Fig. 4. KSI% values for measured and generated 1-min DNI series

6. Conclusions

A new methodology for transforming series of typical daily solar direct normal insolation values into series of typical high-frequency (10-minutes or less) solar DNI years has been developed and validated. This constitutes a relevant step in the quest for the definition of an efficient and robust general scheme for the generation of large series of high-frequency synthetic TMYs which can be entered into CSTP plant energy production models to compute not only the average long-term annual energy production of a CSTP plants but their associated variability or probability distribution, which in turn can be used in probabilistically-oriented economic feasibility studies, which will advance the state of the art of the economic assessment methodologies used to analyse commercial CSTP projects.

The developed methodology to generate high high-frequency (10-minutes or less) solar DNI years from series of typical daily solar DNI years and one-year of high-frequency solar DNI measurements is based on the full nondimensionalization of the daily solar DNI curve.

The validation of this methodology against high-quality and high-frequency (1-minute) experimental solar DNI data has provided KSI% values for DNI series similar to those found in the literature for state-of-the-art models, with one major difference regarding the temporal resolution: to the best of our knowledge, this is the first time, that 1-min solar DNI synthetic years have been synthetically produced which cannot be statistically distinguished from measured high-frequency years.

Other approaches presented in the literature shows that the KSI (%) between measured and modeled solar irradiance datasets are much higher for DNI than for GHI, indicating a worst fit in DNI [14]. Even in modeled DNI datasets with low bias, poor KSI values have been found, indicating that the match in the distribution functions needs further improvement [15]. If one considers that this previous work has been mostly carried out on hourly series and not 1-minute series and that it is reasonable to assume that the goodness of distribution fitting obtained in those studies will decrease at higher temporal frequencies, the relevance of the results presented in this paper are highlighted.

Future works must be directed to the improvement of the enveloping DNI curve model, for example based on enveloping measured curves. Moreover, for the application of the proposed methodology for increasing the DNI frequency, generation of a number of synthetic years must be carried out at daily DNI scale. There are existing methodologies to generate long term GHI series [16, 17], and also synthetic procedures to increase frequency of montly GHI series [18, 19]. The combination of these synthetic generation procedures with existing models to obtain DNI values from GHI must be investigated in order to achieve a realistic daily DNI series to which the methodology presented and validated in this paper could be applied. Furthermore, the generation of high-frequency solar DNI years should be followed by the generation of the corresponding values of the other relevant meteorological variables needed to compose a typical TMY year. This, perhaps, can be approached using schemes similar to the ones proposed by Meteonorm [20].

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