Performance Analysis of 22 Solar Radiation Models and their Classification based on New Validation Methodology

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***Abstract*— Up to now, most validation studies have been based on the MBE and RMSE, and therefore, focused only on long and short terms performance to test and classify solar radiation models. This traditional analysis does not take into account the quality of modeling and linearity. In our analysis we have tested 22 solar radiation models that are capable to provide instantaneous direct and global radiation at any given location Worldwide. We introduce a new indicator, which we named *Global Accuracy Indicator* (GAI) to examine the linear relationship between the measured and predicted values and the quality of modeling in addition to long and short terms performance. Note that the quality of model has been represented by the T-Statistical test, the model linearity has been given by the correlation coefficient and the long and short term performance have been respectively known by the MBE and RMSE. An important founding of this research is that the use GAI allows avoiding default validation when using traditional methodology that might results in erroneous prediction of solar power conversion systems performances.**

***Keywords*— Solar energy, Solar radiation models, Clear sky radiation models, Validation methodology**

I. Introduction

For solar-based renewable energy technologies such as solar thermal or photovoltaic conversion systems, the basic resource or fuel available is solar radiation. Therefore, knowledge of the solar-radiation is essential for the proper design of these power systems. The best method is the long-term measured data at the selected site. However, the lack of radiation measuring stations and networks dictates the need for developing solar radiation models.

Based on the literature, solar radiation models can be divided into two groups. The first one is the decomposition models which are a correlation models that predict the beam or diffuse radiation using other solar radiation measurements. These models are good and more accurate for high clearness index but need global solar radiation data so that they cannot be useful where meteorological station is not available. [1-2]

Contrary to the first group, parametric models are very helpful when measuring stations do not exist. This group predicts direct, diffuse and global irradiances from atmospheric data; moreover they are better than decomposition models when these latter data is accurate [1-3].

In this article the performance of 22 parametric solar radiation models are investigated and validated. These models are selected because they can predict instantaneous or short-term direct, diffuse and global irradiances from limited information on the optical properties of the atmosphere.

II. Selected Radiation Models

A. *Bird Model*

The Bird model was originally developed in 1983 and updated in 1986 [4]. It includes transmittance of atmosphere for Rayleigh scattering, aerosol attenuation, water vapor absorption, ozone absorption, and uniformly mixed gas absorption. Nowadays, there are many parametric models that are based on it, of a particular interest, Iqbal Model C, METSTAT, DLR – modified Iqbal C and CSR models. This well-known model has been used to assess the solar resource over various parts of the world, and to provide the clear sky baseline hourly irradiance for Perez's SUNY satellite model, itself at the core of the 10-km gridded 1998–2005 radiation data of the National Solar Radiation Data Base (NSRDB) update, and of similar data for the Indian sub-continent.

B. *Iqbal Model C*

The model C is a significant variant of the Bird model, where, in particular, the aerosol optical depth (AOD) of the latter is replaced by a specific AOD at 380 and 500 nm.

C. *Modified Iqbal Model C*

This is a variant of Iqbal C. It has been modified and adapted by the German Aerospace Center (DLR). Minor modifications in the air-mass pressure correction factor and the perceptible water formulas have been made. This model has been used by DLR to develop the SOLEMI dataset. SOLEMI is a commercial dataset that offers time series of satellite-derived irradiance data for Europe, Africa and Asia.

D. *METSTAT Model*

This model has been developed by the National Renewable Energy Laboratory (NERL) to produce the original 1961–1990 US NSRDB as well as the 1991–2005 ground-based radiation data for its update released in 2007. The METSTAT model has a deterministic algorithm that may be combined with statistical features so that correct frequency distributions of hourly irradiances can be obtained, despite the use of daily or monthly-average turbidity and cloud input data

E. *CSR Model*

The CSR is stand for the Climatological Solar Radiation. The CSR model is a variant of METSTAT and it has been used to derive datasets and maps of monthly-average irradiations at 40-km resolution for the USA and many other countries, particularly under the auspices of the SWERA project.

F. *Hoyt Model*

This parametric model has been proposed by (Mani and Chacko, 1980; Mani and Rangarajan, 1982) to derive tables of potential solar irradiance for India. The original version of this model (Hoyt, 1978) depended on tabulated data to describe two important functions. Another version of Hoyt's model is Iqbal's Model B that has replaced all tabulated data with simple fitting functions. These fits are used here because they appear closer to the original data than those independently proposed by (Choudhury, 1982).

G. *ESRA Model*

The ESRA is one of the most important European solar radiation models and it has the pivotal role in mapping the solar resource in Europe and bordering countries. Moreover, its original version forms the basis for the latest edition of the European Solar Radiation Atlas. The ESRA model has a key role in mapping the solar resource in Europe and bordering countries. It also constitutes the backbone of the r.sun routine for the open-source GRASS-GIS computer software. Note that the r.sun capabilities have been used to obtain topography-based maps of solar irradiance over Europe and Africa and can also serve to evaluate the potential of solar applications at high spatial resolution.

H. *Heliostat – 1 Model*

The Heliostat – 1 has been developed within the European Heliosat project that assessing solar irradiance from remote-sensed cloud data provided by the Meteosat satellites. The model is made up of separate algorithms for direct irradiance (Page,1996) and diffuse irradiance (Dumortier, 1995). Successive versions have been appeared like Heliostat – 2 and Heliostat – 3, but there is not a perfect consensus on their numbering scheme, particularly in the case of the older versions.

I. *Atwater and Ball Model*

The Atwater and Ball clear sky model accounts for perceptible water, pressure, ground albedo, sky albedo, air mass, and broadband aerosol optical depth to model the transmittance impacts of aerosols and water vapor. The model can also be used to estimate the irradiance with cloud cover [4].

J. *Davies and Hay Model*

The expressions for ozone transmittance, and water vapor absorption, were taken from Lacis and Hansen model [10]. The transmission due to Rayleigh scattering was presented in tabular form, thus we used the Bird model expression for in this model.

K. *Davies and Hay Model*

This is an old complex model.

L. *HLJ Model*

The HLJ is stand for Hottel, Liu and Jordan because of the combination between Hottel model for direct transmittance and of Liu & Jordan's diffuse transmittance formula. This model is initially proposed by Hottel and then it has been applied to assess clear sky solar radiation for numerous locations around the World.

M. *Kumar Model*

The Kumar model is used to provide the backbone for the Solrad and Shortwave routines of the ArcInfo GIS software which have been have been developed for GIS applications in agriculture and ecology. These routines are written in Arc Macro Language (AML). This model is partially based on the Kreith – Kreider and HJL models.

N. *Ineichen and Perez Model*

O. *Fu and Rich model*

This model is simpler than Bird-type models because it requires only the site's elevation and the solar zenith angle. The Fu and Rich model has been developed for GIS applications. More in-depth, it is the backbone of Solar Analyst, a component of the Spatial Analyst routine, part of ESRI's ArcGIS software. As of its version 9.2

P. *ASHRAE Model*

The ASHRAE model is relatively simple and it has been widely used by the engineering and architectural communities to calculate solar heat gains and cooling loads in buildings, or isolation of solar energy systems. It is based on original empirical work conducted in the 1950s and 1960s (ASHRAE, 1972). The main advantage the ASHRAE model is that does not depend on any atmospheric data and hence most users usually apply the model anyway. A tabulated data was used to estimate the solar radiation until its 2009 edition, when a completely new methodology was introduced.

Q. *Kasten Model*

The Kasten model takes into account the atmospheric turbidity and elevation.

R. *Meinel Model model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

S. *Laue model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

T. *Kasten–Czeplak (KC) model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

U. *Haurwitz model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

V. *Berger–Duffie (BD) model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

W. *Adnot–Bourges–Campana–Gicquel (ABCG) model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

X. *Robledo-Soler (RS) model*

This is a simple clear sky model based on measurements for a site location and simple parameters.

III. Performance Analysis

A. *Experimental Data*

The selected 22 parametric clear sky models are compared to measured data for New Delhi climate to analysis their performance, and therefore, test their accuracy and each model's sensitivity to geographic, atmospheric and astronomic parameters, and also to time dependence.

The typical data for New Delhi climate is presented in table below. Long term monthly-mean hourly global radiation data for the selected location are obtained from hourly global radiation by averaging individual hourly values for each month over a period eleven years. The long term monthly-mean daily global irradiation is obtained as the sum of each individual hourly irradiation for that day. The solar radiation data have been collected for the period of 1991-2001 from India Meteorology Department (IMD) Pune, India.

The results, which are outlined in table below, have been obtained using a thermoelectric pyranometer. The pyranometer used are supposed to be calibrated once a year with reference to the World Radiometric Reference (WRR). Critical information such as calibration history, instrument changes, data quality control process, and shading due to obstructions in the horizon, is simply not available for the selected station. Therefore it is to be expected that some data sites have larger uncertainties, with possibly more incorrect or missing data than others.

B. *Prediction vs. Experiments*

Figure 1 shows the Mean global solar irradiance predicted by the selected 22 models for New-Delhi. For simple solar radiation models all input data are estimated using mathematical formulation. Most complex models input are also, however, some default values have been used like aerosol single-scattering albedo.

Figures 2 show the MBD, ABS MBD, RMSD and the U95 for each model. The lowest RMSE is achieved by Berger–Duffie and ASHRAE models (#18, #21) with 11%. The HLJ, DPP and Robledo-Soler models (#12, #15, #20) are not far behind with an RMSE of 12%. In the third class rank the (#6, #17, #19, #22); these are followed by Kasten (#7) model with 14%; and Bird (#2) and KC (#16) with 15%. In the fifth class rank Iqbal model C (#1) together with Modified Iqbal model C with 15%.

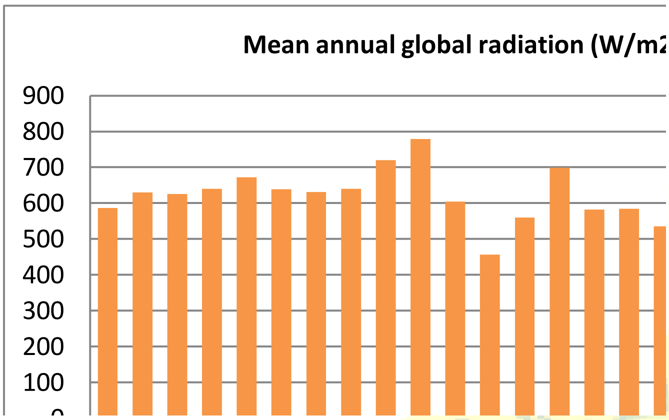

Figure1. Average mean global solar irradiance (W/m2) predicted by 22 models vs. measured

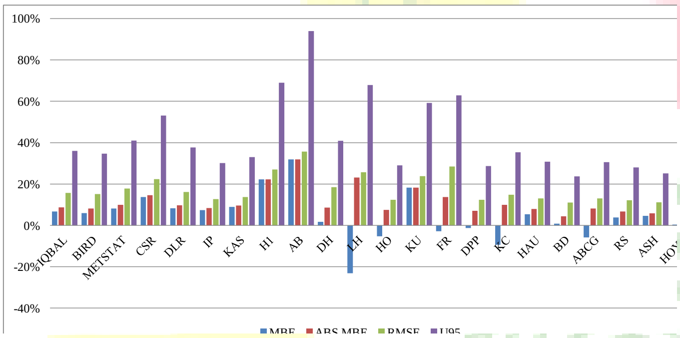

Figure2. Annual Average statistical indicators (%) for global radiation predicted by 22 models

taking into account the quality and linearity of the model, we found that this well known model ranks fourth. The DPP (#15) model rank second with 4 10^{-5}, followed by Hoyt (#22) model with 5 10^{-5}. Some of the clear sky models perform very poorly, such as Heliostat-1 (#8), Atwater and Ball (#9) and Lacis-Hacen (#11) with GAI greater than 10^{-4}. Note that for some models like Fu and Rich model (#14) has very small bias errors, smaller than ±3% but it ranks the 18th. That is why traditional validation methodology is not perfect and can provide wrong judgment.

Using the GAI, we conclude that models with lower MBD (e.g. Fu and Rich, MBD=-2.85%) could not be more accurate than other models such as ABCG with MBD=-5.78%. This latter model ranks eighth so that it has better quality modeling, higher linearity and more accurate short term performance than the Fu and Rich even though the MBD is relatively higher. Note that for several models with low MBD, we can observe that the low MBD results by averaging underestimates of solar radiation in some months with overestimates in other months. With the GAI we can avoid these default errors that might provide wrong test and thus results in erroneous prediction of solar energy systems performances.

One of the most important founding of this analysis is that simple and semi-physical models with fewer inputs like Berger–Duffie and ASHRAE perform unexpectedly better overall than those which require various atmospheric inputs like Bird-type models.

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
GAI (E5)	17	12	28	182	35	32	60	1,538	8,492	10	2,281	17	616	191	4	41	25	3	15	13	6	5
RMSD (%)	16	15	18	22	16	13	14	27	36	19	26	12	24	28	12	15	13	11	13	12	11	13
Classification	10	6	12	17	14	13	16	20	22	5	21	9	19	18	2	15	11	1	8	7	4	3

Table3. Annual average GAI and RMSD

The lowest MBE is Hoyt (#22) with 0.34% followed by Berger–Duffie model (#18) with -0.80%. The Berger–Duffie model is a simple model that requires only one input i.e. zenith angle. This model has also the lowest RMSD as Ashrae model. From figures 2 we have concluded that Berger–Duffie model is the best model that can provide more accurate information about global solar radiation in New Delhi. As indicated by the negative values for MBD, on average all of the models under-predict the amount of GHI.

Table1 confirms that Berger–Duffie is the most accurate model since it has the lowest GAI. Based on the traditional performance tests (i.e. MBD and RMSD), it has been observed that ASHRAE model ranks second, however, when

IV. Most finding

In this study we have introduced a new statistical indicator which we named the Global Accuracy Indicator GAI to validate and test the accuracy of 22 solar radiation models. The GAI is also useful for classifying solar radiation models since it have higher accuracy (in the order of 10^5).

The present analysis has been pointed out that default in validation when using the traditional methods can be avoided with the GAI.

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