VALIDATING CLEAR-SKY IRRADIANCE MODELS IN FIVE SOUTH AFRICAN LOCATIONS

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Abstract

Global horizontal solar irradiance is the maximum solar radiation coming in all directions from a cloudless sky incident at a location and time. This paper evaluates and validates clear-sky models in different locations of South Africa from measured global horizontal irradiance compared to estimated values by these models. The measured data consists of a one-year period in one-minute resolution of GHI at five different stations, namely, Stellenbosch, University of Fort Hare, Vuwani, University of Free State and Pretoria. Four simple (Haurwitz, Berger-Duffie, ABCG, Kasten Czeplak) and three complex (Ineichen − Perez, Bird − Hulstrom, Simplified Solis) clear-sky irradiance models are considered for this paper. The statistical metrics Mean Absolute Error and Root Mean Square Error are used to assess the precision and accuracy of these models. We observed that there is a correlation between the number of input parameters and the performance of the models.

1 Introduction

Clear sky models are distinguished as a group of models with various formulae that have the capability of estimating ground solar irradiance [1]. The estimated irradiance arising from these models is given as either one or a combination of the irradiance components known as direct, diffuse and global. These models vary in complexity and have been proposed by a variety of researchers. In the present study, the models used are categorized as simple or complex models. The simple clear sky models investigated for this study are those of Haurwitz (H) [2], Berger-Duffie (BD) [3], Adnot–Bourges–Campana–Gicquel ($ABCG$) [4] and Kasten–Czeplak (KC) [5]. These models incorporate only the solar zenith angle parameter which produces the global horizontal irradiance (GHI) component. The Ineichen–Perez (IP) [6] , Bird Hulstrom (BH) [7] and Simplified Solis (SS) [8] on the other hand are complex models that consists of several input parameters. One would normally expect complex models to be more accurate compared to the simple clear sky irradiance because they incorporate a number of input parameters such as ozone, aerosols, water vapour, precipitable water, Linke Turbidity, elevation (altitude), airmass and atmospheric optical depth, usually at specific wavelengths.

The characterisation of solar irradiance under clear skies is necessary for determining the performance of solar energy systems (both thermal and electrical energy generation), including the output of a solar photovoltaic system [9]. For solar energy system designs, the clear sky models can basically be used because of their correspondence with the modelled device's optimal power output [1].

There is growing interest in these models, and that has resulted in the development of many models that differ in their predictability and level of accuracy [10]. The accuracy of these models is dependent on their input parameters to produce good estimates in different locations. In order to be able to conduct feasibility studies for solar energy systems in places where irradiance measurements are not available, these ground based models can be applied to minimize the costs instead of building measuring stations. Thus, is it important to select models that perform better and are more accurate to account for clear days with high or low aerosol loads experienced in different local conditions. These models have been used in many places around the world, but the parameters embedded in them are sometimes more suited to the site conditions of the location for which they were developed, and do not necessarily represent South African atmospheric conditions [11]. Hence, it is important to validate these models locally.

The calibration that leads to these model's validation includes an empirical process that computes the relevant attenuation parameters. For certain environments input parameters such as Linke turbidity, site elevation and airmass can be adjusted. This is done to account for the attenuation of the incident solar radiation scattered by atmospheric constituents and absorbed by gases.

1.1 Overview of the study

There are seven physical and empirical models used in the present study. The station measured and clear sky model estimated GHI values are compared to provide a better fit. These models were investigated for five stations in South Africa. They were all evaluated using the statistical method metrics for analysing their performance to determine which model performed the best overall and which one performed well at all specific locations. The Python PVLIB simulation tool was used to work with these models [12].

2 Modelling clear-sky days

In literature, researchers have provided different definitions of a clear sky day. Sivkov (1971) described it as a day that is perfectly cloudless and assumes an average transparency of the sky [13]. The Louche *et al* [14] definition of a clear sky day is cloudless and free of haze. Most of these definitions are, however, specific to the methods in which these researchers were identifying the clear sky days. These models are limited in their capability of covering clouds that are not in the optical path of the instruments that measure the solar terrestrial radiation [13]. In this present study, the relevant definition is from Reno *et al* [15] , which defines a clear sky day as a day without any visible clouds. These days are identified using empirical and physical clear sky irradiance models. Thus, a clear sky day is represented by a plot of measured GHI vs time (i.e in minutes) which produces the smooth-varying diurnal curve.

2.1 Global horizontal irradiance

The prediction of the solar irradiance reaching the Earth's surface is complicated by the variability of meteorological conditions in the atmosphere. Before the radiation reaches the ground there is attenuation caused by the matter in the atmosphere. This is due to the processes of reflection, scattering and absorption. The radiation received at the earth's surface is usually measured in three different components by a horizontal surface.

The global horizontal irradiance (GHI) is a combination of both direct normal and diffuse horizontal irradiance. It is measured using a horizontal pyranometer. Under clear skies it is the maximum solar radiation incident in a specific place and time at earth's surface when there are no clouds. The direct or beam radiation passes through the atmosphere to the surface straight forward from the solar disk without any scattering or reflection. A pyrheliometer is the instrument that measures the direct normal irradiance (DNI). Radiation that is scattered in different directions by the particles and molecules in the atmosphere is known as the diffuse irradiance. When it is received by a horizontal surface it is known as diffuse horizontal irradiance (DHI). It is measured by the pyrheliometer with a disk blocking the direct irradiance. Theoretically, the direct irradiance DNI is given by

$$I_{dni} = \int_{all\lambda} I_\lambda d\lambda$$

whereas the diffuse DHI is as follows

$$I_{dhi} = \int_{I_{dni}\lambda} I_{\lambda,scatter} d\lambda$$

lastly, the global horizontal parameters

$$I_{ghi} = \cos\theta_z * I_{dni} + I_{dhi}$$

where θ_z is the solar zenith angle which is a positional parameter and I_λ is the irradiance at λ wavelength.

2.2 Crucial parameters for models

This paper deals with clear sky irradiance models ranging from simple to very complex. Where both of them are different to one another according the number of parameters they require to function. The simple models do not require any meteorological parameter as input [16]. Models that are more complex, however, do require such parameters.

Radiation under clear sky is attenuated due to continuum scattering by atmospheric molecules and absorption by gases such as ozone, carbon dioxide and oxygen [14]. This causes a necessity in models to obtain a specific minimum level of accuracy. These models are more accurate if the atmospheric or astronomical parameters are known. The models that are chosen for this study require a number of parameters. Among those parameters, the external ones are the solar elevation h and the extraterrestrial radiation I_{ext}. Considering all the models that are used in this research study the other input variables are: airmass AM, altitude h, Linke Turbidity T_L, optical atmospheric depth OAD, ground level atmospheric pressure (p), precipitable water (w), solar zenith angle θ_z.

While the solar zenith angle is a crucial parameter for all the selected models for this study, the Ineichen and Perez model also takes into account the airmass, altitude and Linke Turbidity as shown in Table 1. The Simplified Solis model has parameters such as optical atmospheric depth (OAD), atmospheric pressure p, and

#	Model name	Year	θ_z	α_s	h	P	ρ	AM	μ_o	w_p	T_L	τ_a	Total
1	H	1946	•										1
2	BD	1979	•										1
3	ABCG	1979	•										1
4	KC	1980	•										1
5	IP	2002	•		•			•			•		4
5	BH	1981	•			•	•	•	•	•		•	7
7	SS	2006		•		•				•		•	4

Table 1: **Input data for the models used in this present study which are represented by the following list: h solar elevation of the site, solar apparent elevation α_s, ground level atmospheric pressure p, albedo ρ, absolute airmass AM, ozone O_3, precipitable water in (cm) w, Linke Turbidity Coefficient T_L and atmospheric optical depth at specific wavelengths δ_λ.**

the solar zenith angle. Lastly, the Bird Hulstrom model comprises of OAD at specific wavelength, ozone O_3, zenith angle θ_z, and albedo ρ.

2.3 Clear-sky models

Models for this present study were chosen by taking into account the availability of meteorological and other data which are input variables for them. In prior studies these models have been used and validated over four decades [1]. Consequently, that provides an opportunity to investigate and validate them in different local conditions.

2.3.1 The four 'simple' models

All simple clear sky irradiance models incorporate the solar zenith angle parameter.

Haurwitz

$$I_{ghi} = 1098 \cos(\theta_z) exp[-0.057/\cos(\theta_z)] \quad (1)$$

where θ_z is solar zenith angle and I_{ghi} is the solar global horizontal radiation.

Berger–Duffie

$$I_{ghi} = 1350[0.70 \cos(\theta_z)] \quad (2)$$

Adnot–Bourges–Campana–Gicquel

$$I_{ghi} = 951.39 \cos^{1.15}(\theta_z) \quad (3)$$

Kasten Czeplak

$$I_{ghi} = 910 \cos(\theta_z) \quad (4)$$

2.3.2 Ineichen – Perez

Ineichen – Perez [6] developed clear sky models for the beam and GHI components. The formulation for these models includes empirical adjustment parameters (b, a_1, a_2) and account for turbidity using the Linke turbidity.

$$I_{bnc} = bI_{ext} exp[-0.09AM(T_L - 1)] \quad (5)$$

where T_L is the Linke Turbidity, I_{ext} extraterrestrial irradiance and AM is the airmass which can obtained from the Kasten and Young [17] formula;

$$AM = \frac{1}{\cos(\theta_z)}[1 - 0.0012(\sec^2\theta_z - 1)] \quad (6)$$

In this equation θ_z is the apparent zenith angle.
The equation to compute GHI under clear sky by I - P is;

$$I_{ghi} = a_1 \cos(\theta_z) I_{ext} exp[-a_2 AM(f_{h1} + f_{h2}(T_L - 1))] \quad (7)$$

The above equation comes from Reno *et al* [15] with the input parameters that are given the description below, where:

$a_1 = 5.09 \times 10^{-5} + 0.868$

$a_2 = 3.92 \times 10^{-5} + 0.0387$

$f_{h1} = exp(-h/8000)$

$f_{h2} = exp(-h/1250)$

$T_L = \frac{1}{\cos(\theta_z)}[1 - 0.0012(sec^2\theta_z - 1)]$

The f_{h1} and the f_{h2} parameters incorporate the altitude h of the location of the model in metres.

2.3.3 Bird Hulstrom

According to Gueymard [18], this model is the most used broadband clear-sky model in literature. It requires several input variables which include aerosol optical depth at a specific wavelength of 700 nm and 300 nm, and absorption of uniformly mixed gases represented by T_A, T_W, T_U, T_O, T_R, and T_{AA} which are aerosol extinction, water vapour extinction, transmittances due to uniform gases, Rayleigh scattering, ozone, and aerosol scattering, respectively.

$$I_{dni} = 0.9662 I_{ext} T_A T_W T_U T_O T_R \quad (8)$$

$$I_{dhi} = 0.79 I_{ext} T_O T_U T_W T_{AA} \quad (9)$$

$$I_{ghi} = (I_{dni} \cos(\theta_z) + I_{dhi})/(1 - \rho_g \rho_s) \quad (10)$$

where ρ_s is sky abledo and ρ_g is the ground albedo.This model computes three components which are the DNI, DHI and GHI.

2.3.4 Simplified Solis

This model was developed by Ineichen [8] and it is capable of producing clear sky predictions for direct, diffuse and global radiation. However, the model can compute the global radiation estimate without incorporating the other two components, hence:

$$I_{ghi} = I_{ext} exp(-\tau_g/(cos(\theta_z)^g))cos(\theta_z) \tag{11}$$

where I_{ext}, τ_g, and g are extraterrestrial irradiance, global optical depth, and fitting parameter, respectively.

3 Data analysis

3.1 Data from all locations

The seven models were used to attempt to reproduce one-minute-resolution GHI data from five South African locations: Stellenbosch, University of Fort Hare (UFH), Vuwani, University of Free State (UFS) and Pretoria (CSIR). Figure 1 shows these location across the provinces of South Africa. The data of the Pretoria station was obtained from the roof top of the CSIR Energy Centre, building 34, whereas the data from the other four stations were measurement data from the Southern African Universities Radiometric Network (SAURAN) database [19] (http://sauran.net/).

Figure 1: **The SAURAN locations that are used as part of this research project. Including the Pretoria station.**

3.2 Selection of clear sky days

In this study, only one minute resolution data was used to select clear sky days with clear sky irradiance models. The method used for this research study on selecting clear sky days was based on an observing these days from measured data where an output of GHI can be extracted. Through observing these days from the measured data, a smooth-varying diurnal curve was produced.

Site name	CSIR	UFH	Stellenbosch	Vuwani	UFS
Elevation (m)	1381	540	119	628	1491
Latitude	-25.750	-32.784	-33.928	-23.131	-29.111
Longitude	28.278	26.845	18.865	30.424	26.185
Data start	Jan 2018	Jan 2018	Jan 2018	Jan 2018	Jan 2014
Data end	Dec 2018	Dec 2018	Dec 2018	Dec 2018	Dec 2014

Table 2: **Information detailing the measuring stations from SAURAN and from the roof top of the CSIR Energy Centre, building 34. Table 2 shows the name of the station location, altitude (m), latitude and longitude. The resolution from all of the data periods obtained is in 1 min intervals.**

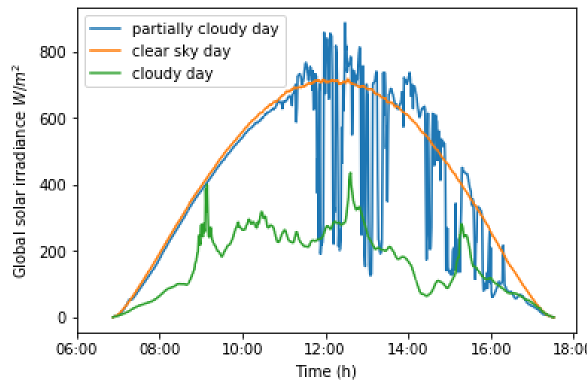

Figure 2: **This graph represents a plot of GHI vs. time(s) at one location. Measured values of GHI from Pretoria Energy Centre, 03/07/2018 (blue line), 06/07/2018 (orange line), 08/07/2018 (grey line).**

Figure 2 shows a difference between days that vary in clearness. When selecting the days as clear, the fit of the models and measured GHI had to correspond as shown in Figure 3.

3.3 Statistical indicators for model accuracy

The statistical metrics were used for this research project to evaluate the precision and accuracy of the models. These are the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE), given by equation 12 and 13, respectively.

$$MAE = \frac{1}{n}\Sigma_{i=1}^{n} \mid P_i - O_i \mid \tag{12}$$

$$RMSE = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i)^2} \tag{13}$$

where P_i are the estimated values of the model, O_i are the measured values at specific time i, and n is the number of values.

These two metrics were used to evaluate both the simple and complex models. Figure 3, comprises of simple

Location	ABCG		H		KC		BD		IP		SS		BH	
	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE
UFH	1.99	1.33	2.18	1.63	4.22	3.29	7.05	5.52	1.66	1.17	1.64	1.15	1.67	1.20
CSIR	2.08	1.62	2.32	1.75	4.00	3.11	6.44	5.01	2.93	2.23	1.83	1.44	2.02	1.69
Stellenbosch	1.96	1.31	2.55	1.98	4.22	3.31	6.17	4.81	1.09	0.83	1.89	1.30	2.23	1.64
Vuwani	3.89	3.28	1.97	1.33	3.65	2.71	5.75	4.34	1.61	1.06	1.91	1.14	1.89	1.22
UFS	1.44	1.17	1.64	1.35	3.66	2.98	6.02	4.82	2.78	2.15	1.48	1.22	1.37	1.11

Table 3: **Clear sky days evaluated for global horizontal irradiance in five locations using Root Mean Square Error and Mean Absolute Error. RMSE and MAE are represented in percentages (%).**

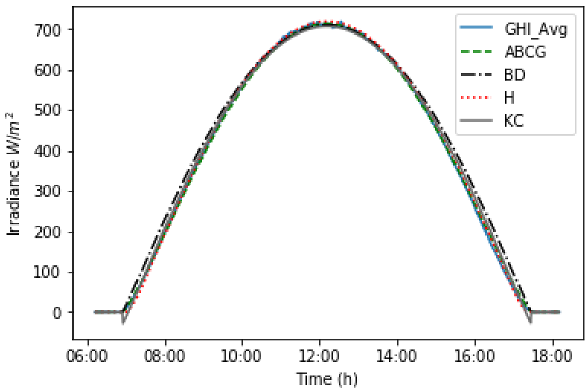

Figure 3: **Comparison of the performance of four simple clear sky irradiance models against one minute data at CSIR on 3 July 2018.**

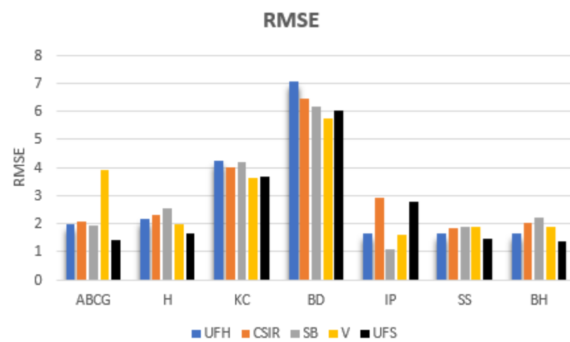

Figure 4: **The horizontal axis represents models implemented in different locations which are: UFH - Univeristy of Fort Hare, CSIR - Council of Science Industrial Research, SB - Stellenbosch University, V - Vuwani Research Centre, UFS - University of Free State.**

clear sky irradiance models fitted to the measured GHI. Observing the KC and BD model at different times of the day, they have a tendency of overestimating the solar irradiance at sunrise and sunset. However, during the middle of day the irradiance by the two models is underestimated. In order to rank the simple models performance using RMSE and MAE. Table 3 shows that H and ABCG with MAE of $< 2\%$ and $< 4\%$ and RMSE of $< 3\%$ and $< 4\%$, respectively, which are indicated by Table 4 as excellently performing models. On the other hand, the KC and BD models performed good to average for the extraction of clear sky days. They had an MAE of $< 4\%$ and $< 6\%$ and RMSE of $< 5\%$ and $< 8\%$, respectively.

The complex models which required more input variables from meteorological and astronomical data performed excellently in all locations (see Table 3 and 4). On the other hand, there were days and stations where both complex and simple models performed equally well in providing the best fit. The comparison of the Solis Simplified, Bird – Huldstrom, and Ineichen – Perez models were also evaluated as performing similar to the simple models. In particular, the ranking using the statistical indicators were the same. Thus, the order of performance and accuracy showed that the best model was the SS with an overall MAE of $< 1.4\%$ and RMSE $< 2\%$. The BH model was also an excellent model with MAE of $< 1.7\%$ and RMSE $< 3\%$. Lastly, the IP model with MAE of < 2.3 and RMSE $< 3\%$ performed third best in overall models as it out-performed every model in lower altitudes, however, in high altitude the SS, BH, H and ABCG performed better than it.

3.4 Model validation across stations

The statistical indicators allowed the models to be classified easily from excellent to poorly performing. As clearly indicated on Table 1, the model that performed the best overall was the Bird – Huldstrom model which needs only seven input parameters. This model had an overall average RMSE and MAE of $< 5\%$ and $< 2\%$ respectively, across all locations.

Figures 4 and 5 shows a plot of RMSE and MBE, respectively. The two figures provide more details regarding the evaluation for choosing models that will be suitable to select clear sky days. The five models which are the Bird – Huldstrom, Ineichen – Perez, Solis Simplified, ABCG, and H enable the selection of clear days. However, Gueymard [18] suggested that a complete validation of clear sky irradiance models in a location requires more than three years worth of data. Therefore, in this study the

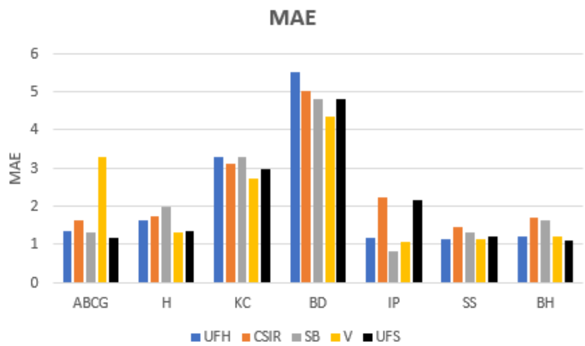

Figure 5: **The horizontal axis represents models implemented in different locations which are: UFH - University of Fort Hare, CSIR - Council of Science Industrial Research, SB - Stellenbosch University, V - Vuwani Research Centre, and UFS - University of Free State.**

validation is regarded as narrowing or eliminating from the large number of models the ones that have potential to provide excellent clear sky period estimations in different locations.

Global horizontal statistical indicators		
Model accuracy	RMSE	MBE
Poor	$\geq 15\%$	$\geq 10\%$
Average	$\geq 10\%, < 15\%$	$\geq 5\%, < 10\%$
Good	$\geq 5\%, < 10\%$	$\geq 2\%, < 5\%$
Excellent	$< 5\%$	$< 2\%$

Table 4: **Criteria for the evaluation of the performance of these models.**

4 Discussion

In parts of the country where irradiance measuring stations are not available some of the excellent performing clear sky irradiance models can be used. Their performance and accuracy is shown in the figures that compare the RMSE and MBE values when evaluating the performance of these models. The relationship observed from Table 1 and Figures 4 and 5 unsurprisingly indicates that the models with more parameters performed better. However, in most cases these parameters are not explicitly measured in other stations. Then a good input parameter approximation becomes essential. Using a visual comparison of the GHI vs time curve, adjusting parameters of the models provides good approximating values for a particular day.

Fig. 4 and Fig. 5, which provide the RMSE and MAE statistics, visually reveal as expected that the complex models (i.e. Simplified Solis, Ineichen - Perez, and Bird – Hulstrom) perform excellent or good in some of the locations compared to the simple models (H, KC, ABCG, and BD). The results and criteria in Table 3 and 4, respectively, presents a way to group these varying models. Consequently, the ranking according to how well they perform are: SS, BD, and I-P with RMSE of $< 5\%$ and MAE of $< 2\%$ in overall locations. On the other hand, the simple models that performed good (see statistical indicators in Table 4.) were the H and ABCG. Thus, the remaining KC and BD models in these locations were average in their performance.

The geographic location of where the models are used is very important for clear sky irradiance models. This is apparent in the change of performance of the models in Fig. 4 and Fig. 5 from each location. Table 2, shows the difference in altitude of these locations. In all these models, the Ineichen-Perez model only accounts for this parameter and from the observational analysis there is a difference in performance. The Stellenbosch and UFH locations (in lower altitudes) have the lowest values, whereas, CSIR-Pretoria and UFS (in high altitudes) have the highest values of RMSE and MBE. This comparison demonstrates that the Ineichen - Perez model is less accurate when it is used in high altitudes. However, that would require further investigation with a substantial amount to data using different sites altitudes.

Using only five clear sky days for each location is not enough to validate the models chosen for this study.

5 Conclusion

The global horizontal irradiance measured data producing a smooth-varying diurnal curve from different sites in South Africa was evaluated against simple and complex clear sky irradiance models. With the use of parameter approximation, five models including simple (ABCG and H) and complex (Ineichen – Perez, Bird – Hulstrom and Simplified Solis) had empirical fits with low RMSE and MAE. This implies that these models are optimum for adoption in different parts of the country.

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