ESTIMATION OF GLOBAL SOLAR RADIATION BY JOHNSON-WOODWARD METHOD

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Abstract

Solar radiation is the fundamental renewable energy source that sustains the biosphere and drives its self-organization. Reliable solar radiation data sets are essential to the work of energy planners, engineers and agricultural scientists. Thus solar radiation is a driving variable for a wide range of processes in both natural and human systems. The number of meteorological stations equipped with radiation measuring equipment, as compared to other meteorological parameters, is very few. Furthermore, the present statistics and information on such stations have many record errors. As a result, designing models and reviewing of techniques to estimate the solar radiation are quite useful for applied studies. The objective of this study is the estimation of the global solar radiation, using the Johnson-Woodward (JW) methodology for the first time in Iran and comparing the results derived from this method with meteorological data. This method is an empirical parameter and its sole inputs are the geographical latitude and sunshine hours. To achieve this goal, initially, the model's empirical parameter was calculated, using the radiation data quality controlled and then using this parameter, the daily global solar radiation was estimated. For this estimation, the data from four synoptic meteorological stations in Tehran Province with long–term radiation statistics was used. To evaluate the estimation results, the statistical methods on error comparison such as Root Mean Squared Error, Mean Bias Error, Mean Absolute Error and correlation coefficient, were used. The results show that the above method used in estimating the solar global radiation has a high degree of accuracy. This model has an overall superior performance for synoptic meteorological stations in Tehran Province.

Key Words: Global Solar Radiation, Johnson-Woodward Method, Sunshine hours, Tehran Province.

1.Introduction

The main elements of developing the applied research on solar energy in any given area , crop climate models, photosynthesis, evapotranspiration, surface energy budgets, the estimation for water consumed by the plants and the usage of the new energies, are study of solar radiation and the estimate thereof.

Determination of the solar energy capacity of a region requires that extensive radiation measurements of high quality be made at a large number of stations covering the major climatic zones of the region. Hence the substantial spatial and temporal gaps that exist in the meteorological data record pose a handicap for a significant number of applications where solar radiation data are required. Since these data are expensive to collect (or effectively impossible to collect when absent from historical records), there is a consequent demand for methods that can estimate the variables needed. On-site measurement of solar radiation is much rarer than for other meteorological variables(temperature and/or sunshine hours). There have thus been several approaches developed that use these variables within models to estimate solar radiation. Therefore, qualification of this renewable energy capacity effectively through the empirical models plays an important role in developing renewable energy technologies and the sustainability of natural resources. This paper follows on from previous research that performance of model to estimate solar radiation, and that concluded the Johnson–Woodward (JW) model, estimating solar radiation values from sunshine hours duration. The Johnson–Woodward model has a single empirical parameter (F) that indicates the intensity of diffuse solar radiation from cloudy skies.

2. Approach

This paper builds on a previous investigation that compared a number of models that derived solar radiation from other meteorological variables [16]. Johnson et al. [8] developed a sunshine duration to solar radiation conversion method for use in tropical rainforest canopies. This method was applied by Woodward et al. [22] to pastures in New Zealand. This model accounts for latitude, solar declination, elevation, day length and atmospheric transmissivity on a daily basis and has only daily sunshine hours (hours) and latitude as input. The method contains a single empirical parameter representing the relative intensity of diffuse solar radiation from cloudy skies. This paper concluded using data from four Tehran Province meteorological stations that overall the Johnson–Woodward method [8, 22] was superior to other methods. There were several caveats to this conclusion. First that the superiority was likely to be application-specific. Second, that the JW method has a small but systematic bias in prediction with a seasonal pattern. Third, that the empirical calibration factor (F) was site-specific and would need to be estimated for stations without solar radiation records. The authors are unaware of the JW model being used elsewhere, other than the studies by the original developers of Johnson et al. [8] and subsequently by Woodward et al. [22], despite its promising potential [17].

3. Materials and methods

3.1. Meteorological data

Solar radiation data are important tools for many areas of research and applications in various engineering fields, where the number of solar observation stations is poor. The availability of meteorological parameters, which are used as the input of radiation models, is the important key to choose the proper radiation models at any location. Unfortunately, solar radiation measurements are not easily available for many developing countries for not being able to afford the measurement equipment and techniques involved. Because the pyranometers have high cost and need supervision, few stations have this equipment. Although the meteorological measurements are done in many cities of Iran, during the decades little research have been done in the field of meteorological data to complete scientific research details, It is the case that the climatic and meteorological data in most regions of Iran are limited and they should be expanded. In Iran, as elsewhere, the availability of solar radiation data from meteorological stations is more restricted than for precipitation and temperature. Sunshine duration is more widely recorded. Very few stations in Iran observe daily precipitation, air temperature and solar radiation together. Four meteorological stations, Tehran-north, Imam Khomeini Airport ,Tehran-mehrabad and Karaj, in Tehran Province, were selected as they hold long-term records for precipitation, maximum and minimum air temperature, solar radiation and sunshine hours. At other stations (Geophysics Tehran, Firouzkooh, Hashtgerd, Abali, Chitgar and Doshan Tappeh) it was not possible to test the JW model due to the absence of sunshine duration or solar radiation data. These stations had fewer years when sunshine duration or solar radiation data were available than temperature data. Errors, duplicates and anomalies in the original data were identified during the database loading process. Stations were only included if they had daily observed maximum and minimum air temperature, global solar radiation and sunshine hours data for a minimum of five years. At other stations of Tehran it was not possible to test the JW model due to the absence of solar radiation and/or sunshine hours data. Having conducted quality control and necessary statistical tests, we used different observed meteorological data as the input of the employed radiation models. Measured data were taken mainly from the Islamic Republic of Iran Meteorological Office (IRIMO) data centre [10]. The quality control of daily global solar radiation was employed using statistical tests (i.e. run-test; higher limits of daily sunshine hours and daily limits of extra-terrestrial daily solar radiation of the location). The run-test and limit check were carried out on the daily observed total solar radiation data to make sure that the data are homogeneous and the variations of daily observed total solar radiation are caused only by climatic influences and not by other sources of errors (e.g. systematic errors caused by instruments, calibration problems, data transferring, etc.).

4. Johnson–Woodward (JW) method

1.4. Solar radiation estimation

Johnson et al.[8] developed a sunshine duration to solar radiation conversion method for use in tropical rainforest canopies. This model to calculate the daily rate of net canopy photosynthesis in response to irradiance and atmospheric CO_2, incorporating adaptation to growth conditions, is presented. Net photosynthesis is calculated using daily mean direct solar and diffuse sky radiation components, estimated from total daily solar radiation. The present development requires an estimate of the fraction of the day receiving full sun, h_s/h, also known as the per cent possible sunshine.The irradiance information available from meteorological data usually consists of either the mean daily irradiance, J_0(Wm^{-2}PAR), or the total daily irradiance, Φ($Jm^{-2}day^{-1}$PAR). Then Johnson et al. [8] model was applied by Woodward et al. [22] to pastures in New Zealand. In this model a practical water balance model is presented. The model uses daily rainfall and potential evapotranspiration estimates to predict changes in the water content in two overlapping soil zones.Potential evapotranspiration can be estimated from daily climatic data such as temperature, radiation, or sunshine hours, using any one of a number of models. Johnson et al. [8] and Woodward et al.[22] use sunshine duration to predict solar radiation. The model accounts for latitude, solar declination and elevation, day length and atmospheric transmissivity on a daily basis and has only daily sunshine duration as input. Total daily irradiance (J_0) is given by:

$$h J_0 = h_s J_{0,s} + h J_{0,d} \tag{1.4}$$

where h is day length, h_s is the sunshine duration, $J_{0,s}$ is the direct beam and $J_{0,d}$ the diffuse components. Day length in hours is calculated by:

$$h = \frac{24}{\pi}\cos^{-1}\ (-\tan\lambda\tan\delta) \qquad (2.4)$$

where λ is the latitude and δ is the solar declination in radians. Solar declination for each day of the year is given by:

$$\delta = -0.4084\cos(2\pi\frac{d+10}{365}) \qquad (3.4)$$

where d is the Julian day of year. Following Campbell [5], the direct beam component $J_{0,s}$ is given by:

$$J_{0,s} = 1367\frac{2p}{\pi}\sin\phi(\tau^{\frac{1}{\sin}}) \qquad (4.4)$$

where p is the fraction of radiation in full spectrum sunlight (here 1 is used) and 1367 is the solar constant ($Jm^{-2}s^{-1}$). The clear sky transmissivity, τ, varies according to the number and efficiency of scattering particulates. φ is the solar elevation at noon:

$$\sin\varphi = \sin\lambda\sin\delta + \cos\lambda\cos\delta \qquad (5.4)$$

The method detailed in Woodward et al.[22]finds the clear sky transmissivity (τ) by:

$$\tau = 0.64 + 0.12(2\Pi\frac{d-174}{365}) \qquad (6.4)$$

The diffuse portion of total irradiance is represented by $J_{0,d}$ (cloud conditions and from blue sky scattering simultaneously), following List [13], can be calculated by:

$$J_{0,d} = J_{0,p}\,(f_{blue}\,(1-c) + f_{cloud}\,c) \qquad (7.4)$$

Where $J_{0,d}$ is the mean daily irradiance due to diffuse light. c is the mean daily fraction of cloud cover, where invoking the Taylor Hypothesis [18] gives: c = 1 - (h_s/h), being a dimensionless value between 0 (complete cloud cover) and 1 (no cloud cover). $J_{0,p}$ is the total clear sky mean daily irradiance:

$$J_{0,p} = \frac{1367\sin\varphi}{2\pi}(1+\tau^{\frac{1}{\sin\varphi}}) \qquad (8.4)$$

$J_{0,p}$ is the potential total clear sky mean daily irradiance. Of course, contributions to J_0 will also be made by diffuse radiation from clouds. The relative importance of short wave radiation from clouds will increase as the cloud cover increases or, equivalently, as h_s decreases. Let f_{cloud} **,** represent the cloud diffuse radiation, as a fraction of $J_{0,p}$ and let f_{blue} the clear sky diffuse radiation, again as a fraction of $J_{0,p}$. Where the relative intensity of radiation from blue sky is

$$f_{blue} = \frac{1-\tau^{\frac{1}{\sin\varphi}}}{1+\tau^{\frac{1}{\sin\varphi}}} \qquad (9.4)$$

The value of f_{cloud} represent the relative radiation intensity under cloud conditions:

$$f_{cloud} = F\,f_{blue} \qquad (10.4)$$

Thus total daily irradiance (J_0) is given by:

$$\Phi \approx \frac{3600\, h\, J_0}{10^6\, p} \tag{11.4}$$

Note that daily irradiance Φ is often measured and expressed as total short wave radiation. It is common to assume that PAR(Photosynthetically Active Radiation) is one-half of the total solar radiation. This method gives an estimate of solar radiation from sunshine hours data. Aside from the improved accuracy of prediction, an additional benefit of calculating daily direct and diffuse radiation explicitly is that daily photosynthesis can then also be calculated [8]. If sunshine data are available, however, solar radiation can be more accurately estimated using the method described in Johnson et al. [8], as follows. The JW model was refined and tested by Rivington et al. [17] and found to produce good results for the regression coefficient of determination at three stations. However, the physical mechanism used in observation of sunshine hours can result in large measurement errors, in the range of ±20% [1].

2.4. Empirical parameter (F) Estimation

Johnson-Woodward model has a single empirical parameter representing the relative intensity of diffuse solar radiation from cloudy skies. To determine the parameter F for each site, values were fitted for each day per year to give daily optimized F values [12]. The mean value per year was calculated, and then the mean of these values used to represent a particular site. Yearly and long term average values for F are then derived from the daily values. The method optimizes daily values of F such that the JW method accurately predicts the measured solar radiation values using sunshine hours as the input. Daily solar radiation values can then be estimated for every year for which sunshine hours are available, using the JW model. Woodward et al. [22] determined an F of 1.11 for New Zealand. For the UK there was a range in mean F between 0.69 and 0.87 [16]. The JW model imposes a base-line amount of diffuse radiation, variable with h, such that an input of 0 sunshine hours will still produce a value of irradiance for a given day of year. A previously published method [16] for estimating the F parameter was used to derive yearly values per site. The method optimizes daily values of F such that the JW method accurately predicts the measured solar radiation values using sunshine hours as the input. Yearly and long term average values for F are then derived from the daily values. Daily solar radiation values can then be estimated for every year for which sunshine hours are available, using the JW model [8, 16]. In the overall scope of Tehran, there was a range in mean F between 0.4246 and 0.8452. The F parameter controls the relative contribution of diffuse radiation on cloudy days, and is thought to determine the seasonal over- and under-estimation errors.

5. Results and discussion

5.1. Assessment method

Model validation was made by the statistical methods on error comparison such as Root Mean Squared Error(0 to infinity), Mean Bias Error, Mean Absolute Error and Correlation Coefficient(-1 (full negative correlation) to 1 (full positive correlation)).Conventional methods for model assessment have provided an indication of the magnitude of differences between the observed and estimated values. For this method, the averages of errors (MAE, MBE, RMSE) between the model results and the observed data were computed. MBE and MAE show the deviations between the measured and the estimated solar radiation, which have to be kept as minimum as possible to select the best method. The MBE and

RMSE provide, respectively, the long-term performance of an equation and the short-term performance of an equation. Introduced errors in input data can manifest themselves in terms of a model's incorrect estimations of quantities, rates, patterns, timing and synchronization of events. Appropriate location-specific data are also essential for model calibration. The performance of the JW model were initially tested using single statistical indices. Estimated values were compared with observed solar radiation by regression analysis. For selected of locations, the difference between mean daily observed versus estimated solar radiation was calculated from all available years at the site. This difference in daily means helps to illustrate the temporal distribution of mean daily errors over the period of a year, indicating systematic model behaviour. Results for the basic level statistics are given in Table 1.

Table 1. Geographical information of four synoptic meteorological stations in Tehran Province and the RMSE, MBE and R values in estimating daily solar radiation

Station	**Altitude**	**Longitude**	**Altitude(m)**	**Year**	**RMSE**	**%RMSE**	**MBE**	**%MBE**	**R**
Tehran North	35.47	51.37	1548.2	2004	2.56	13.93	-0.46	-2.49	0.971
				2005	2.33	12.98	0.30	1.65	0.958
				2006	1.91	10.89	-0.72	-4.08	0.978
				2007	1.98	11.68	-0.82	-4.85	0.974
				2008	1.44	8.20	·0.05	0.28	0.985
Imam Khomeini Airport	35.25	51.10	990.2	2004	1.78	10.08	0.14	0.82	0.979
				2005	2.33	13.17	0.30	1.72	0.955
				2006	2.15	11.26	-0.82	-4.29	0.978
				2007	1.75	7.29	-0.19	-1.03	0.986
				2008	2.09	11.26	-0.70	-3.75	0.971
Tehran Mehrabad	35.41	51.19	1190.8	1985	1.95	11.01	0.16	0.90	0.976
				1986	2.19	13.08	0.31	1.84	0.967
				1987	1.83	10.54	-0.03	-1.73	0.977
				1988	2.19	11.66	-1.00	-5.34	0.977
				1989	2.01	10.63	-0.53	-2.81	0.983
Karaj	35.55	50.54	1312.5	1985	1.85	10.22	-0.73	-4.03	0.980
				1986	1.97	11.25	-0.76	-4.32	0.979
				1987	1.82	10.43	-0.59	-3.35	0.983
				1988	2.77	15.18	-0.57	-3.14	0.955
				1989	1.74	14.40	0.10	0.85	0.915

5.2. Conclusions

The design and estimation of the performance of any solar energy system requires the knowledge of solar radiation data obtained over a long period of time. The network of stations measuring this parameter is sparse in many countries. In Iran, only few stations have been measuring the daily solar radiation. It is, therefore, necessary to approximate solar radiation from commonly available climate parameters such as sunshine hours, relative humidity, maximum and minimum temperatures, cloud cover and geographic location. However, most of the models require weather parameters which may not be available at many stations. Over the last two decades, using simple radiation models has been an interesting task to estimate daily solar radiation in Iran, where the number of solar observation stations is poor. In this work, different radiation model (Johnson-Woodward) has been revised to predict the daily solar radiation on horizontal surfaces in various stations in Tehran Province. Using JW model, we estimated the daily global solar radiation for four locations in Tehran. The predicted solar radiation data have been compared against a long-term experimental daily radiation observed at four solar stations. Model validation was made by means of Mean Bias Error (MBE), Root Mean Squared Error(RMSE), Mean Absolute Error and Correlation Coefficient. MBE shows the deviations between the measured and the estimated solar radiation. The JW model gave the best overall results in terms of individual indices.

This model (JW) has only daily sunshine hours (hours) and latitude as input and contains a single empirical parameter (F), representing the relative intensity of diffuse solar radiation from cloudy skies. The parameter F shows limited variability with geographical location. As the results of this study show correlation coefficients ranging from 0.915 to 0.986 are very close to one. Results showed that the JW model has a systematic bias, where the model over-estimates in the winter and under-estimates in the summer. The research has shown that the JW model is robust and has relatively low sensitivity to variations in the F parameter. Thus the application of the JW method at stations without on-site solar radiation measurements is feasible. The JW model imposes a base-line amount of diffuse radiation, variable with h, such that an input of 0 sunshine hours will still produce a value of irradiance for any given day of year. Where sunshine hours data are available, it is preferable to use the JW model to estimate solar radiation, rather than the models based on air temperature. The JW model has a built-in function of estimating a base level of diffuse solar radiation under cloudy conditions for each day of the year, determined by day length, so that days with 0 h of sunshine still result in approximations of solar radiation values. The results suggest that the model requires further refinement to reduce the over-estimation caused by the daily base level diffuse radiation component estimation ($J_{0,d}$), and an increase in the estimates resulting from the direct beam radiation estimation ($J_{0,s}$) in the summer period. Thus the results have demonstrated that each model is capable of making good estimates at some locations and poorer ones at others.

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