

Performance Evaluation of Models Established for the Estimation of Diffused Solar Radiation: Case Study Lahore, Pakistan

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Abstract: A suitable design of solar power project requires accurate measurements of solar radiation for the site of investigation. Such measurements play a pivotal role in the installation of PV systems. While conducting such studies, in general, global solar radiation (GSR) is recorded, whereas diffuse component of solar radiation on a horizontal surface is seldom recorded. The objective of the present study is to assess diffuse solar radiation (DSR) on horizontal surfaces by using polynomial models for Lahore, Pakistan (27.89 N, 78.08 E) and by correlating clearness index with diffuse fraction. The established models are compared with some of the existing models from the literature. Performance of models is evaluated by employing five goodness-of-fit (GoF) tests that are, mean bias error (MBE), root mean square (RMSE), Coefficient of Determination (R^2), Mean Absolute Percentage Error (MAPE) and Akaike's Information Criterion (AIC). The comparison of the results of goodness-of-fit tests with those of existing models indicate that the models established in the present study are performed better as compared to the existing models. The values of statistical error analysis further suggested that a cubic model with a good accuracy of 97.5% and AIC of -22.8 is relatively more suitable for this climatic region for estimating diffuse solar radiation. The study shows that the model developed is in good agreement with Elhadidy and Nabi model with an accuracy of 96.1% and AIC of 4.4 and satisfactory results are obtained for Lahore. The findings can help to give a generous understanding of solar radiation in order to optimize the solar energy conversion systems. The results of this study provide a better understanding of the associations between global solar radiation, clearness index and diffused fraction for the region under study.

Keywords: Global horizontal radiation, diffuse solar radiation, polynomial models, clearness index, Lahore.

Introduction

For the implementation of solar power projects, the knowledge regarding the solar irradiance data and their components at study site must be known prior to the design of the project. Solar energy is environmentally friendly, plentiful and easy to utilize. Due to the geographical location of Pakistan and long sunshine duration, solar energy has a significant role to play in generating electrical energy. Average value of global solar radiation over Pakistan ranges from 1500 W/m²-day to 2750 W/m²-day throughout the year. GSR has two components (i) DSR and (ii) direct solar radiation. Correct knowledge of GSR and its components for the site under study is of practical importance in designing and execution of a solar energy conversion system (Kumar and Uman, 2005). On the other hand, in developing countries, like Pakistan which are technically and financially constrained, the diffuse radiation data are not available for many sites. In such scenarios DSR data are usually predicted using modeling and simulation technique, using various meteorological and geographical data as input variables for models (Halawa et al., 2014).

Oliveira et al. (2002) constructed models based on linear regression approach for estimating hourly, daily and monthly DSR in the city of Sao Paulo, Brazil. Soares et al. (2004) applied artificial neural network in estimating DSR. As input parameters to the network,

the authors used GSR and other meteorological parameters. Shamshirband et al. (2016) estimated DSR by the SVM-WT model. These techniques are complex and required a bulk amount of data. Additionally, a number of studies were conducted to develop mathematical models for the estimation of DSR on a horizontal surface. These studies used a range of parameters as input such as sunshine hours, relative humidity, declination angle and latitude. (Wang et al., 2018; Jamil and Akhtar, 2017; Sabzpooshani and Mohammadi, 2014; Li et al., 2012; Li et al., 2012; Li et al., 2011).

Liu and Jordan (1960) originate a correlation between GSR and extraterrestrial solar radiation. Using this ratio, they estimated the diffuse component of global horizontal solar radiation for USA. This technique of estimating DSR is used by a number of research groups. Iqbal (1980) modified the idea of Liu and Jordan (1960) and determined the DSR in Canada. Ulgen and Hepbasli (2009) estimated the monthly mean daily DSR using eight models for three big cities in Turkey. In case of the unavailability of observed data, DSR is determined by fitting a model to data which is available for regions with similar climate conditions. Torres et al. (2010) compared the performance of various models in estimating hourly DSR in Pamplona, Spain. Erbs et al. (1982) conducted a study which correlates diffuse and GSR on a horizontal surface using clearness index. Lam and Li

(1996) obtained a linear relation between GSR and mean DSR by using clearness index.

The studies conducted in this regard for Pakistan, Ulfat et al. (2012) developed empirical model for Islamabad, Pakistan for the determination of diffuse component using a relationship containing diffuse fraction and clearness index. Ahmed et al. (2009) estimated global and DSR for Hyderabad, Sindh, Pakistan using models given by Liu and Jordan. Ahmad and Naqvi, (1981) in an analysis, proposed a model for Karachi, Pakistan, for the assessment of DSR using correlation between diffuse fraction and clearness index and their model was based on regression analysis.

The current study is based on the construction of mathematical models to estimate DSR using correlation between clearness index and diffuse fraction. The study also aims at comparing the performance of these models with existing models based on the measured data recorded for Lahore using statistical indicators. Nevertheless, the study is significant in a sense that up-to-date data are used for developing the proposed model enumerating some useful results.

Materials and Methods

Study Area and Data Description

The measuring station is located in Lahore city, at Latitude N 31.6944°, Longitude E 74.2442°, with its altitude 220 m above mean sea level. Lahore is characterized as a semi-arid climate. In the present study Diffuse and GSR data for Lahore are used. The data were collected from the study project ESMAP (2015). Measurements were performed from October 2014 to January 2017. Measuring equipment is located on the top of the Center of Energy Research at the University of Engineering and Technology (UET) campus in Lahore, Pakistan. The station was outfitted with Kipp and Zonen CMP10 pyranometer for Global horizontal radiation measurement and CSPS Twin-RSI for DSR measurement. These measurements were recorded through a Campbell Scientific CR1000 data logger. The data are recorded at intervals of 10 minutes. In the preprocessing phase, the recorded data were averaged, first on hourly basis and then on monthly basis.

Models in Literature

Some models are chosen from literature for comparison purposes. These models correlate diffuse fraction and clearness index. The selection of these models is based on their performance and climate conditions prevailing in the regions for which these models were designed. Table 1 lists these selected models for comparison. In these equations, H_d is monthly mean daily DSR ($\text{MJ}/\text{m}^2\text{-day}$), H is monthly mean daily GSR ($\text{MJ}/\text{m}^2\text{-day}$), H_0 is monthly mean daily extraterrestrial radiation ($\text{MJ}/\text{m}^2\text{-day}$), and K_T is

the ratio of global to extraterrestrial solar radiation ($K_T = H/H_0$). Diffuse fraction K_d is the ratio of diffuse to GSR ($K_d = H_d/H$). The average daily extraterrestrial solar radiation on a horizontal surface can be estimated for different latitudes from the solar constant, the solar declination and day of the year using Eq. 1 as presented by Duffie and Beckman (2013). In the following equation the average day of the month is considered according to Klein (1977).

$$H_0 = \frac{24}{\pi} \times 3600 I_{sc} \left[1 + 0.033 \cos \left(\frac{360}{365} d_n \right) \right] \left[\left(\frac{2\pi}{60} \right) \sin \phi \sin \delta + \cos \phi \cos \delta \sin \omega_s \right] \quad (1)$$

$$\omega_s = \cos^{-1}(-\tan \delta \tan \phi) \quad (2)$$

Where angle δ can be calculated by the Eq. 3

$$\delta = 23.45 \sin \left[360 \frac{284 + d_n}{365} \right] \quad (3)$$

Monthly average estimated value of H_0 , observed values of H , and of H_d are shown in Figure. 1. The maximum value of H_d is observed to be $11.56 \text{ MJ}/\text{m}^2\text{-day}$ in July while minimum value of H_d is $5.42 \text{ MJ}/\text{m}^2\text{-day}$ found in December. Figure 2a shows monthly variation of clearness index (K_T) and diffuse fraction K_d . As observed, April and May are more clear months of the year ($K_T = 0.57$), the lowest value of clearness index ($K_T = 0.39$) is found for the month of January. The lowest value of diffuse fraction ($K_d = 0.4$) is observed during the month of April, whereas July shows maximum value of diffuse fraction ($K_d = 0.63$). A high value of clearness index indicates reasonably good availability of solar radiation, which provides good opportunity for solar energy utilization. In Figure 2b diffuse fraction (K_d) is plotted as a function of clearness index (K_T) and a reciprocal trend is observed between these two parameters.

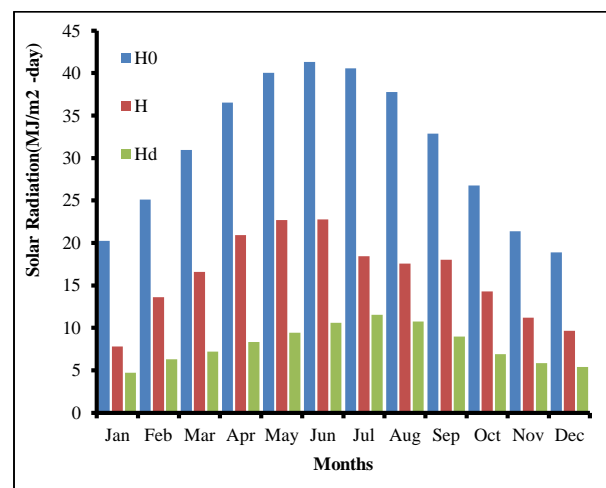


Fig. 1 Plot of monthly solar radiation as monthly mean global horizontal radiation (H), extraterrestrial solar radiation (H_0), and DSR (H_d) for Lahore.

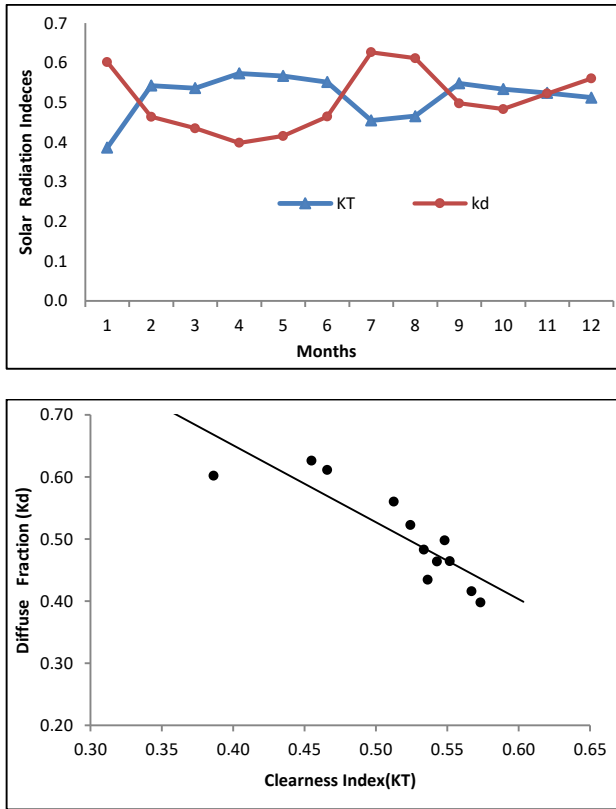


Fig. 2 (a) Monthly Variations of the K_T and the K_d . (b) Scatter plot of K_d versus K_T .

Table 1 The models picked from literature for current study with the author and study location

Model No	Regression Equation	Author and locations
M1	$\frac{H_d}{H} = 1.0 - 1.13 K_T$	Page (1967) for USA
M2	$\frac{H_d}{H} = 0.999 - 1.1283 K_T$	Alnaser (1989) for Bahrain
M3	$\frac{H_d}{H} = 1.102 - 1.299 K_T$	AL-Hamdani et al . 1989 for Baghdad
M4	$\frac{H_d}{H} = -1.271 + 8.925 K_T - 10.5 K_T^2$	Elhadidy and Abdel-Nabi (1991) for Saudi Arabia
M5	$\frac{H_d}{H} = -6.5707 + 42.611 K_T - 81.113 K_T^2 + 48.849 K_T^3$	Ulgen K and Hepbasli (2009) for Turkey
M6	$\frac{H_d}{H} = -1.390 - 4.027 K_T + 5.531 K_T^2 - 3.108 K_T^3$	Abdalla(1987) for Doha (Qatar)
M7	$\frac{H_d}{H} = 1.2313 e^{-2.2(K_T)}$	Sanusi and Abisoye (2013) for Lagos, Nigeria
M8	$\frac{H_d}{H} = -1.018 - 1.167 K_T + 0.024 K_T^2$	Jiang (2009) for China

The proposed models in the present study estimate monthly mean DSR by establishing a correlation between diffuse fraction and clearness index. The coefficients of proposed models are determined using regression analysis on the data of the diffuse fraction (K_d) and the clearness index (K_T) by varying the degree of the polynomials. Proposed models are presented in Table 2.

Table 2 Equations of the models developed using measured data of Lahore station.

Model No.	Model Type	Regression Equation
E1	Linear	$\frac{H_d}{H} = 1.1469 - 1.2396 K_T$
E2	Quadratic	$\frac{H_d}{H} = -1.271 + 8.925 K_T - 10.5 K_T^2$
E3	Cubic	$\frac{H_d}{H} = -6.5707 + 42.611 K_T - 81.113 K_T^2 + 48.849 K_T^3$
E4	Exponential	$\frac{H_d}{H} = 1.7298 e^{-2.398 K_T}$

Model Performance Evaluation

The estimated values are tested against observed values through statistical analysis. The tests performed in this study include the Mean Bias Error (MBE), Root Mean Square (RMSE), Coefficient of Determination (R^2), Mean Absolute Percentage Error (MAPE), and Akaike's Information Criterion (AIC_c). The best model is the one with the lowest AIC_c . These indicators are defined respectively as:

$$MBE = \frac{1}{n} \sum_{i=1}^n (H_{d,i,cal} - H_{d,i,meas}) \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (H_{d,i,cal} - H_{d,i,meas})^2} \quad (5)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \left(\frac{H_{d,i,cal} - H_{d,i,meas}}{H_{d,i,meas}} \right) \right| \times 100 \quad (6)$$

$$AIC_c = n \cdot \ln \left(\frac{1}{n} \sum_{i=1}^n (H_{d,i,cal} - H_{d,i,meas})^2 \right) + 2k + \frac{2K(K+1)}{n-K-1} \quad (7)$$

where $H_{d,i,meas}$ and $H_{d,i,cal}$ are the observed and estimated i^{th} mean value of DSR, k is the number of parameter plus one and n is the number of data points.

Results and Discussion

By using the available measured data for global solar radiation at Lahore station and least square regression method, four models have been developed for the study area. The models are given in Table 2. Models proposed in this study and known models in literature are used for the estimation of monthly mean values of DSR. These estimated values are plotted in Figure 3 and in Figure 4 for all months along with the measured data. As it is clear from Figure 3, the values obtained from the models developed in current study area adequately close to the observed data. Whereas, the values obtained from existing models are significantly far from the observed values, model (M1, M2, M3, M6, M7 and M8) underestimated the H_d values while model (M4) overestimated H_d values (Fig. 4). The performance of models could be verified from scatter plots. Figure 5 is the scatter plot between estimated values of H_d (from the models developed in current

study) and measured values of H_d . The cubic model shows a strong correlation ($R^2 = 0.975$) between estimated and observed values. Figure 6 shows the scatter plots between estimates of H_d values (from models picked from literature) and observed values of H_d . It is clear that Elhaddidy and Nabi (1991) model shows a higher value of Coefficient of Determination ($R^2=0.961$) of correlation and all other plots show poor relationship.

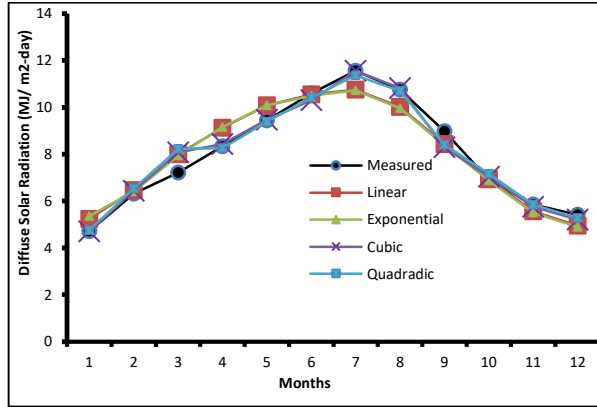


Fig. 3 Plots between estimated values and measured data at Lahore of monthly average daily DSR from developed models.

A thorough analysis has been performed through statistical analysis to assess the performance of all models considered in current study. Table 3 summarizes the results of statistical tests. It is quite evident that the results of current study models are more accurate as compared to the models considered from literature. Further, it is found that the best results are obtained from model E3 (cubic) with Positive bias having $MBE = 0.0025$ MJ/m²-day, $RMSE = 0.34$ MJ/m²-day, $MAPE = 2.83\%$, $R^2 = 0.975$ and lowest AIC (-22.8). Although MBE is least for linear model but, AIC 's test was conducted for all the models, which reveals that AIC is lowest for model E3 (cubic). This confirmed the better performance of the cubic model.

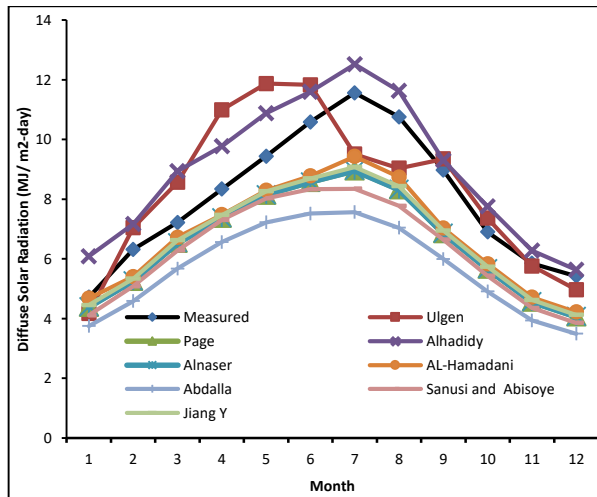


Fig. 4 Comparison among the estimated values from existing models and measured data at Lahore of monthly average daily DSR from the existing models.

Table 3. Performance indicators for the proposed and existing models.

Models	MBE	RMSE	MAPE	AIC	R ²
E1	0.0019	0.56	6.22	-11.0	0.934
E2	0.0220	0.36	3.05	-21.5	0.973
E3	0.0025	0.34	2.83	-22.8	0.975
E4	-0.0247	0.59	6.66	-9.8	0.928
M1	-1.4415	1.59	17.51	14.1	0.946
M2	-1.4432	1.59	17.53	14.15	0.953
M3	-1.2272	1.37	14.76	10.61	0.953
M4	0.9558	1.06	12.65	4.4	0.961
M5	0.3658	1.44	13.82	11.77	0.682
M6	-2.3188	2.48	28.55	24.80	0.921
M7	-1.7102	1.88	20.93	18.13	0.918
M8	-1.3569	1.51	16.45	12.85	0.946

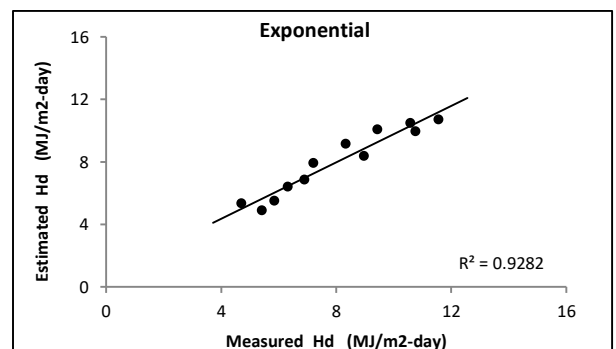
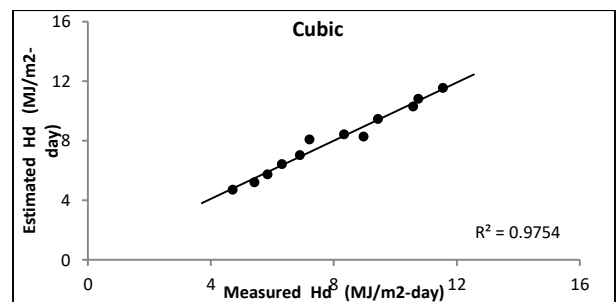
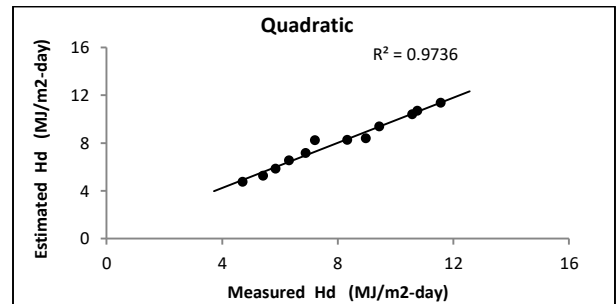
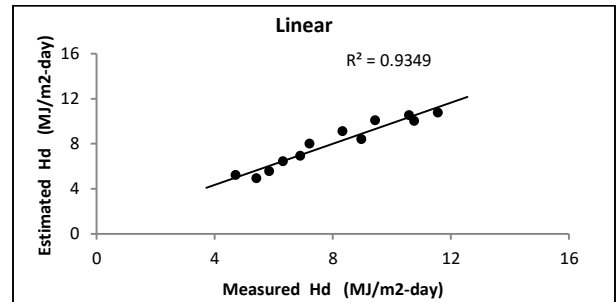


Fig. 5 Plots between the estimated values and measured data for the monthly average daily diffuse solar radiation in Lahore using the four candidate models.

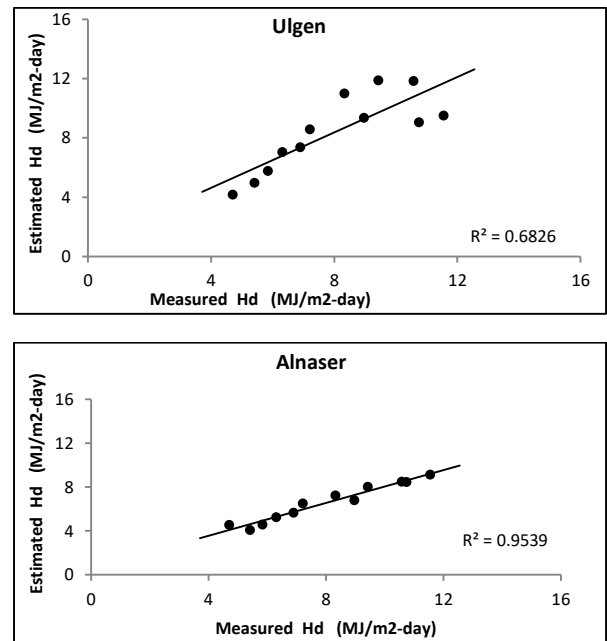
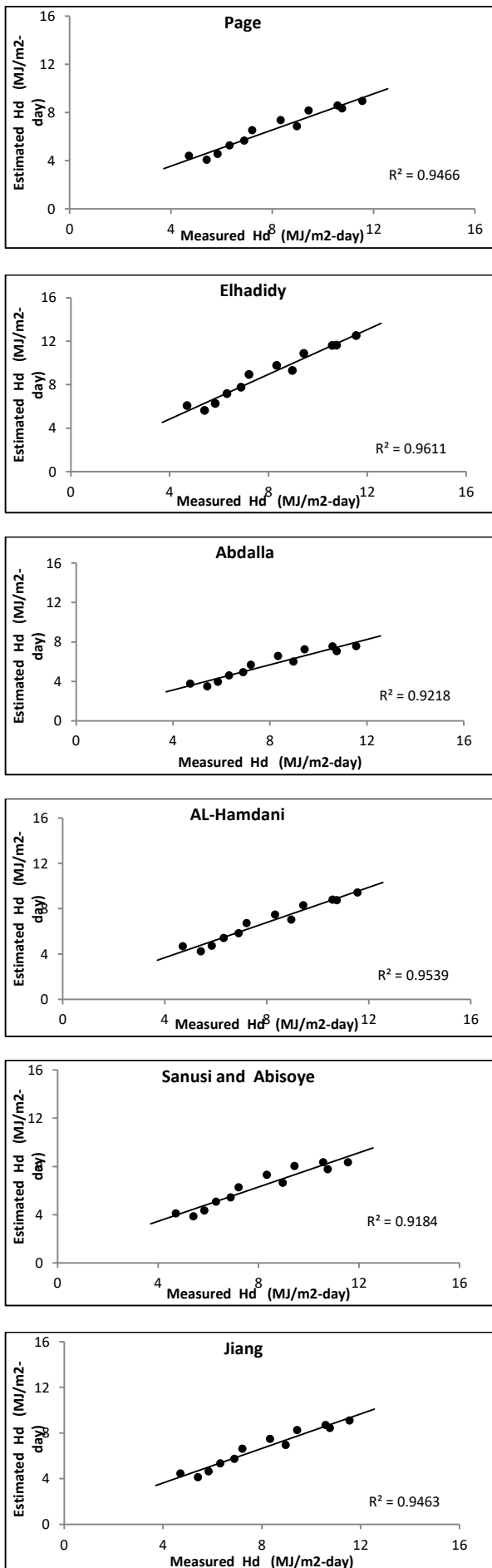


Fig. 6 Plots between the estimated values and measured data using existing models for the monthly average daily DSR in Lahore.

Conclusion

In this study, four new models (linear, quadratic, cubic and exponential) and eight models from the literature have been used to estimate the monthly mean DSR on horizontal surface at Lahore. The comparison between developed models of current study and the models picked from literature has been carried out by using five statistical tests. All the tests were conducted using measured data of Lahore station. The statistical indicators show that the models proposed in the current study performed better than the models picked from literature. Furthermore, it is noted that amongst the proposed models, model E3 delivered the highest performance according to statistical analysis with MBE = 0.0025, RMSE = 0.34, MAPE = 2.83, AIC = -22.8 and R² = 0.975. The study is in good agreement with the diffuse solar radiation model obtained by Elhaddidy and Nabi (1991) and is in good comparison with the observed values for Lahore for diffuse solar radiation with MBE = 0.9558, RMSE = 1.06, MAPE = 12.65, AIC = 4.4 and R² = 0.961. This study was directed with the main objective to produce computationally simple and accurate diffuse radiation models. The estimated method involved incorporating traditional clearness index - diffuse ratio models. In conclusion, this study provides a method for estimating diffuse solar radiation with acceptable accuracy at Lahore and is useful for designing energy production systems using solar energy.

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References

- Abdalla, Y.A. (1987). Solar radiation over Doha (Qatar). *International Journal of Solar Energy*, **5**, 1-9.
- Ahmad, F., Naqvi, S.A., (1981). Characteristic distribution of total, direct and diffuse solar radiation at Karachi. *Pak. J. Sci. Res.*, **24**, 171.
- Ahmed, M.A., Firoz, A., Akhtar, M.W. (2009). Estimation of global and diffuse solar radiation for Hyderabad, Sindh, *Pakistan. Journal of Basic & Applied Sciences*, **5**, 73-77.
- Al-Hamdani, N., Al-Riahi, M., Tahir, K., (1989). Estimation of the diffuse fraction of daily and monthly average global radiation for Fudhaliyah, Baghdad (Iraq). *Solar energy*, **42**, 81-85.
- Alnaser, W.E., (1989). Empirical correlation for total and diffuse radiation in Bahrain. *Energy*, **14**, 409-414.
- Duffie, J.A., Beckman, W.A. (2013). *Solar engineering of thermal processes*, 56. John Wiley & Sons, New York, USA.
- Elhadidy, M.A., Abdel-Nabi, D.Y., (1991). Diffuse fraction of daily global radiation at Dhahran, Saudi Arabia. *Solar Energy*, **46**, 89-95.
- Erbs, D.G., Klein, S.A., Duffie, J.A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy*, **28**, 293-302.
- ESMAP (2017). Data and information obtained from World Bank via energydata.info, under a project funded by the energy sector management assistance program (ESMAP).
- <https://energydata.info/dataset/pakistan-solar-measurement-wbg-esmap>
- Halawa, E., Ghaffarian Hoseini, A., Li, D.H.W. (2014). Empirical correlations as a means for estimating monthly average daily global radiation: a critical overview. *Renewable energy*, **72**, 149-153.
- Iqbal, M., (1980). Prediction of hourly diffuse solar radiation from measured hourly global radiation on a horizontal surface. *Solar Energy*, **24**, 491-503.
- Jamil, B., Akhtar, N. (2017). Comparative analysis of diffuse solar radiation models based on sky-clearness index and sunshine period for humid-subtropical climatic region of India: A case study. *Renewable and Sustainable Energy Reviews*, **78**, 329-355.
- Jiang, Y. (2009). Estimation of monthly mean daily diffuse radiation in China. *Applied Energy*, **86**, 1458-1464.
- Klein, S.A. (1977). Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, **19**, 325-329.
- Kumar, R., Umanand, L. (2005). Estimation of global radiation using clearness index model for sizing photovoltaic system. *Renewable Energy*, **30**, 2221-33.
- Lam, J.C., Li, D.H. (1996). Correlation between GSR and its direct and diffuse components. *Building and environment*, **31**, 527-535.
- Li, H., Bu, X., Lian, Y., Zhao, L., Ma, W. (2012). Further investigation of empirically derived models with multiple predictors in estimating monthly average daily diffuse solar radiation over China. *Renewable Energy*, **44**, 469-473.
- Li, H., Bu, X., Long, Z., Zhao, L., Ma, W. (2012). Calculating the diffuse solar radiation in regions without solar radiation measurements. *Energy*, **44**, 611-615.
- Li, H., Ma, W., Wang, X., Lian, Y. (2011). Estimating monthly average daily diffuse solar radiation with multiple predictors: a case study. *Renewable energy*, **36**, 1944-1948.
- Liu, B.Y., Jordan, R.C. (1960). The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy*, **4**, 1-19.
- Oliveira, A.P., Escobedo, J.F., Machado, A.J., Soares, J. (2002). Correlation models of diffuse solar-radiation applied to the city of Sao Paulo, Brazil. *Applied Energy*, **71**, 59-73.
- Page, J.K. (1967). August. The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records 40S-40N. In *Proceedings of the United Nations Conference on New Sources of Energy: Solar Energy, Wind Power and Geothermal Energy*, 21-31, Rome, Italy.
- Sabzpooshani, M., Mohammadi, K. (2014). Establishing new empirical models for predicting monthly mean horizontal diffuse solar radiation in city of Isfahan, Iran. *Energy*, **69**, 571-577.
- Sanusi, Y.K., Abisoye, S.G. (2013). Estimation of diffuse solar radiation in Lagos, Nigeria. In *2nd International Conference on Chemical, Environmental and Biological Sciences*, 17-18, Dubai (UAE).
- Shamshirband, S., Mohammadi, K., Khorasanizadeh, H., Yee, L., Lee, M., Petković, D., Zalnezhad, E. (2016). Estimating the diffuse solar radiation using a coupled support vector machine-wavelet transform model. *Renewable and Sustainable Energy Reviews*, **56**, 428-435.

- Soares, J., Oliveira, A.P., Božnar, M.Z., Mlakar, P., Escobedo, J.F., Machado, A.J. (2004). Modeling hourly diffuse solar-radiation in the city of São Paulo using a neural-network technique. *Applied Energy*, **79**, 201–214.
- Torres, J.L., De Blas, M., García, A., De Francisco, A. (2010). Comparative study of various models in estimating hourly diffuse solar irradiance. *Renewable Energy*, **35**, 1325-1332.
- Ulfat, I., Javed, F., Abbasi, F.A., Kanwal, F., Usman, A., Jahangir, M., Ahmed, F. (2012). Estimation of solar energy potential for Islamabad, Pakistan. *Energy Procedia*, **18**, 1496-1500.
- Ulgen, K., Hepbasli, A., (2009). Diffuse solar radiation estimation models for Turkey's big cities. *Energy Conversion and Management*, **50**, 149-156.
- Wang, H., Sun, F., Wang, T., Liu, W., (2018). Estimation of daily and monthly diffuse radiation from measurements of GSR: a case study across China. *Renewable Energy*, **126**, 226-241.