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Empirical model based on meteorological parameters to estimate the global solar radiation in Nepal

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Abstract

Solar radiation is the best option and cost effective energy resources of this globe. Only a few stations are there in developing and under developed countries including Nepal to monitor solar radiation and sunshine hours to generate a rational and accurate solar energy database. In this study, daily global solar radiation, and ubiquitous meteorological data (temperature and relative humidity) rather than rarely available sunshine hours have been used for Biratnagar, Kathmandu, Pokhara and Jumla to derive regression constants and hence to develop an empirical model. The model estimated global solar radiation is found to be in close agreement with measured values of respective sites. The estimated values were compared with Angstrom-Prescott model and examined using the statistical tools. Thus, the linear regression technique can be used to develop model at any location in the world. The resultant model may then be used to estimate the missing data of solar radiation for the respective sites and also can be used to estimate global solar radiation for the locations of similar geographic and meteorological characteristic.

Keywords: Global solar radiation; Clearness index; Relative humidity; Temperature; Linear regression Relation; Empirical model.

1. Introduction

Nepal is a land locked mountainous country with a large area of beautiful landscape situated between $26^0$22' to $30^0$27' north latitude and $80^0$40' to $88^0$12' east longitude [1] within a span of 200 km from south to north and about 800 km in east to west [2].

More than 6000 rivers with all river systems draining north to south towards the Ganges [1] in Nepal whereas theoretical, technical and economically feasible hydropower potential has been estimated at about 83000 MW, 45000 MW and 42000 MW respectively [2]. The current installed capacity of power plants connected to the national grid is 693 MW. The electricity consumption and the number of consumers increasing at a rate of approximately 9 % per year [3] which project peak demand of power 1163.2 MW for 2012/2013, 2052.00 MW for 2019/2020, and 3679.10 MW for 2027/2028 [4] whereas generation of additional power plant is almost in sluggish. This gap of supply and demand in energy sector forces Nepal Electricity Authority to load-shedding from 4 hours per day in spring and 16 hours per day in dry season [5].

Fossil fuel reserves in the world have been depleting rapidly [6], even though their uses create negative impact to environment [7]. The construction period for new power generation projects and new import transmission capacities is very long therefore a rapid improvement of energy supply and an urgent supply of power through diesel power plants cannot be expected. The power supply crisis affects public life and especially economic development negatively [3]. On the other hand biomass technology does not work well enough on the comparatively cold high altitude and small hydro turbines need special topographical conditions [2] to set up and run. All these facts claim the transfer of the emphasis to the new clean alternative energy resources to replace costly and not viable sources and ensure sustainable development of the country.

In the fiscal year 2008/09 total energy consumption in Nepal was 410,000 TJ. The consumption coverage data provided by MOF shows 85% coverage by traditional resources (i.e., biomass energy resources), 14 % by commercial sources (petroleum products-9 %, coal-3 % and grid electricity- 2 %) and about 1% by alternative sources (biogas, solar power, wind and micro/pico level hydropower) [8]. The average global solar radiation in Nepal varies from 3.6-6.2 kWh/m^{2}day, sun shines for about 300 days a year, the number of sunshine hours amounts almost 2100 hours per year and average insolation intensity about 4.7 kWhm^{-2} day^{-1} (=16.92 MJ/m^{2}day) [2] it is greater than 4.38kWh/m^{2}day (15.8 MJ/m^{2}day) measured by [7] for Lao PDR. Thus, Nepal lies in a favourable insolation zone in the world even though the data in Nepal was based on one year and few sites [2] but that of Lao PDR was based on few years and throughout the country. So, a long term and many sites' solar energy data are required to authenticate this statement.

Solar energy, in the country like Nepal, is the best and crucial option among the different energies including alternative energy sources. *Based on various facts and factors including global warming deforestation, and climate change (which may deplete the sources of water) Government of Nepal/private sectors have switch the priority of investment to generate the electricity into the solar farming even though per unit cost of electricity from solar energy is relatively higher than that of hydro electricity so far*. Moreover, for rural electrification in Nepal, everyone should have to plan to link up micro-hydro/pico-hydro with solar energy exploitation [9].Thus, an accurate knowledge and database of solar radiation at a particular place and selected sites are important for the development of many solar devices, establishment of solar plant to the proposed site and for estimation of their performance [10].

The radiation reaching the earth surface is modified significantly by clouds [11], water vapor, ice, aerosols, and atmospheric constituents in its intensity and the sunshine duration. The beam radiation (radiation coming directly from the solar disk) is attenuated by the presence of cloud in its path, as well as by the various atmospheric elements. The depletion of the direct beam by the cloud depends on type of cloud, their thickness and number of layers [12]. The radiation scattered by the atmospheric constituents is called diffuse radiation where a portion of this radiation goes back by about 6% of the incident radiation to space, and a portion, about 20% of the incident radiation, reaches the earth surface [13]. The sum of direct and diffuse radiation on the earth surface is known as global/total radiation which is very important for the design of certain solar energy applications [12].

In Nepal like developing countries, the facility of ground based measurement of solar radiation is available only at selected sites whereas meteorological and hydrological data are available at different parts of the country. Certainly the best way of knowing the amount of global solar radiation at the site of consideration is to install pyranometer at many locations in the given region and look after their day to day maintenance and recording, which is a very expensive venture. The alternative approach is to develop a model based on meteorological parameters, where the data can be collected, to estimate global radiation.

The resultant correlation may then be used for locations of similar meteorological characteristics [14]. Thus, developing an empirical model to estimate the global solar radiation using various parameters such as sunshine duration, maximum and minimum temperature, relative humidity, rainfall and geographical location etc. is an essential assignment, for the country like Nepal, which is a vigorous scientific research. So far various models have been developed by a number of researchers with different regression coefficients using linear regression techniques [15] for various countries and for different locations to estimate solar radiation. The most and commonly used model, including Nepal, is Angstrom [16] and modified later by Prescott [17] which is based on sunshine hours [9]. In almost underdeveloped countries temperature and relative humidity are easily measured but the instrument to measure sunshine hours is in a very few locations.

Empirical models which have been used to calculate solar radiation are usually based on astronomical factors, geographical factors, geometric factor, physical factors and meteorological factors [18]. Available literatures relate that there is a very few and limited study done in Nepal to develop the empirical model [9].

In the present study, global solar radiation, meteorological/hydrological data have been used to derive the regression coefficients a, b, c, d to develop a model based on linear regression technique to estimate the monthly mean daily global solar radiation for four sites of Nepal and compare the values with the estimations from the Ref. [5,9,16,17,19].

2. Materials and Method

The raw data of daily solar radiation on horizontal surface for Biratnagar, Kathmandu, Pokhara and Jumla were collected from the archives of the Department of Hydrology and Meteorology, Government of Nepal (DHM/GoN) and Solar Radiation and Aerosol in Himalayan Region (SAHR) project of Institute of Engineering, Tribhuvan University, Nepal. Daily sunshine duration, temperature and relative humidity data for these sites were obtained from Department of Hydrology and Meteorology (DHM)/GoN. The data obtained covered a period of years from 2007 - 2012 for Biratnagar (latitude 26.483^0, longitude 87.266^0 and altitude 72m above the sea level), 2010 - 2012 for Kathmandu (latitude 27.7^0, longitude 86.366^0 and altitude 1337m above the sea level), 2008- 2012 for Pokhara (latitude 28.216^0, longitude 84^0 and altitude 827m above the sea level) and two years, 2011 - 2012 for Jumla (latitude 29.283^0, longitude 82.166^0 and altitude 2300m above the sea level). The most widely used ORIGIN and Microsoft Office Excel software have been used for the data analysis.

2.1 Theory

Microsoft Office Excel was used to process the data in useable/desirable form. The proposed linear regression relation i.e., *empirical model* to estimate global solar radiation which is based on temperature and relative humidity is as below:

$$\frac{\overline{H}_m}{\overline{H}_O} = a + b\,\overline{T} + c\,\overline{T^2} + d\,\overline{RH} \qquad (1)$$

Here, a, b, c, and d are regression constants, $\overline{T}$ is monthly mean daily maximum temperature in Celsius unit, $\overline{T^2}$ is monthly mean daily square of maximum temperature, RH is monthly mean daily maximum value of relative humidity, the ratio $\overline{H}_m / \overline{H}_O$ is monthly mean daily clearness index K_T, and H_o is the daily extraterrestrial radiation on the horizontal surface given by Iqbal [12] as follows:

$$H_o = \frac{24}{\pi} I_{sc} E_o [\frac{\pi}{180}\omega_s \sin\phi \sin\delta + \cos\phi\cos\delta\sin\omega_s] \qquad (2)$$

where, $I_{sc} = \frac{1367\times3600}{1000000}$ MJ/m^{2}h^1, (3) is the solar constant,

$E_o = 1 + 0.33\cos\frac{360N}{365}$ (4) is the eccentricity correction,

N is the day number of the year (DoY)/ Julian day (1 Jan, N=1 and 31st Dec, N=365),

$\emptyset$ is the latitude of the site,

$\delta = 23.45 \sin\left[\frac{360(N+284)}{365}\right]$ (5) is the solar declination,

$\omega_s = \cos^{-1}(-\tan\phi\tan\delta)$ (6) is the hour angle,

$N_d = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) = \frac{2}{15}\omega_s$ (7) is the maximum possible sunshine hours.

2.2 Developing a Model

The first order linear regression equation was employed to analyze the data as given below,

$$a + b\,T + cT^2 + d\,RH = K_T \tag{8}$$

This represent an equation of least square line [20] or first order regression [21] where, $K_T = \frac{H_m}{H_o}$ is a dependent variable called clearness index, and independent variables as maximum value of temperature T, & maximum value of relative humidity RH.

The equation (8) has been multiplied by 1, T, T^2, and RH successively and summing both sides, to obtain the regression constants are as given below:

$$aN + b\sum T + c\sum T^2 + d\sum RH = \sum K_T \tag{9}$$

$$a\sum T + b\sum T^2 + c\sum T^3 + d\sum T\,RH = \sum K_T T \tag{10}$$

$$a\sum T^2 + b\sum T^3 + c\sum T^4 + d\sum T^2 RH = \sum K_T T^2 \tag{11}$$

$$a\sum RH + b\sum T\,RH + c\sum T^2\,RH + d\sum RH^2 = \sum K_T\,RH \tag{12}$$

Three years data of Biratnagar (BRT), four years data of Pokhara (PKR) and two years data of Kathmandu (KTM) & Jumla (JML) separately were used to evaluate regression constants a, b, c, and d which are presented in Table 2.

2.3 Data Analysis

The accuracy of the estimated values by Angstrom-Prescott model and *new model* was tested by using the statistical techniques based on the definition devised by Iqbal [12] which are given below:

$$RMSE = [\{\textstyle\sum_1^n(\overline{H}_e - \overline{H}_m)^2\}/n]^{1/2} \tag{13}$$

$$MBE = [\textstyle\sum_1^n \overline{H}_e - \overline{H}_m)]/n \tag{14}$$

$$MPE = [\sum_1^n \frac{\bar{\bar{H}}_m - \bar{\bar{H}}_e}{\bar{H}_m} \times 100)]/n \qquad (15)$$

$$CC = \frac{\Sigma(\bar{H}_e - \bar{H}_{me})(\bar{H}_m - \bar{H}_{mm})}{[\{\Sigma(\bar{H}_e - \bar{H}_{me})^2\}\{\Sigma(\bar{H}_m - \bar{H}_{mm})^2\}]^{1/2}} \qquad (16)$$

Here n is the total numbers of observations, $\bar{H}_e$ and $\bar{H}_m$ are monthly mean measured and estimated values and $\bar{H}_{mm}$ and $\bar{H}_{me}$ are mean of measured and estimated values respectively. Calculated values of different parameters in organized form with coefficient of regression, R and coefficient of determinant, R^2 derived from the plots for the statistical analysis and correlation coefficient (CC) are presented in the Table 2.
These, earlier stated, statistical indicators are used to examine the performance of the model of solar radiation estimation. In general, low values of root mean square error (RMSE), mean bias (MBE) and mean percentage error (MPE) are expected for the better performance of the model. RSME test provides information on the short-term performance at the same time MBE and MPE test provide information on the long-term performance. The positive and negative values of MBE represent the overestimation and the underestimation [22] respectively of the radiations. Preferably, for the best performance, correlation coefficient (CC), coefficient of regression (R) and coefficient of determinant (R^2) each should be 1.

3. Results and Discussion

Regression technique has been used to determine the coefficients for Biratnagar, Kathmandu, Pokhara and Jumla, presented in Table 2, to develop empirical model. Positive value and negative value of coefficients b and d respectively, for all sites, show the better correlation of solar radiation with temperature and relative humidity i.e., greater the temperature more is the solar radiation & vice versa and greater the relative humidity lesser is the solar insolation and vice-versa.

Table 1 presents the measured and estimated monthly mean daily global solar radiation at four different sites of Nepal where their varies altitude from 72m to 2300m above the sea level and location from east to west part of Nepal. The values were estimated by using the Angstrom-Prescott model and by the new model separately. The minimum measured and model estimated value of monthly mean daily radiation on the horizontal surface were observed in January and December characterized by more cloudy/misty days and relatively farther distance of the Earth from the Sun.

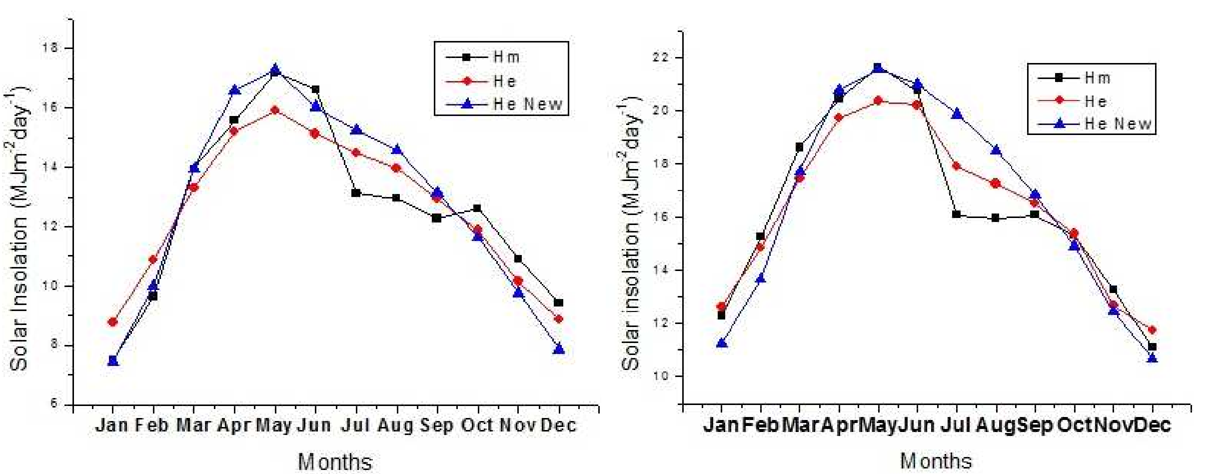

Figure 1: (a) Variation of radiation with months for Biratnagar **(b)** Variation of radiation with months for Kathmandu

Table 1. Monthly Mean daily Measured and Estimated Solar Insolation at four sites.

Month	Biratnagar			Kathmandu			Pokhara			Jumla		
	H_m	H_e	$H_{e\ new}$	H_m	H_e	$H_{e\ new}$	H_m	H_e	$H_{e\ new}$	H_m	H_e	$H_{e\ new}$
JAN	7.49	8.77	7.42	12.31	12.62	11.27	11.27	12.29	11.09	15.07	15.74	13.96
FEB	9.63	10.85	9.98	15.26	14.86	13.71	14.24	14.49	13.78	16.60	17.22	17.11
MAR	13.94	13.28	13.95	18.61	17.46	17.73	16.69	17.18	17.58	22.38	21.83	22.35
APR	15.56	15.18	16.59	20.44	19.73	20.76	18.65	19.45	20.31	22.81	22.61	24.44
MAY	17.18	15.90	17.29	21.64	20.36	21.55	20.95	20.59	21.40	25.21	24.64	26.24
JUN	16.60	15.12	16.03	20.74	20.20	21.01	21.25	20.54	21.09	24.97	24.31	25.68
JUL	13.11	14.46	15.25	16.09	17.90	19.87	18.82	19.04	20.50	19.99	19.89	22.52
AUG	12.95	13.96	14.57	15.96	17.25	18.50	18.71	18.27	19.35	19.23	19.27	21.15
SEP	12.25	12.94	13.12	16.09	16.52	16.84	16.98	17.00	17.40	20.54	20.21	19.24
OCT	12.59	11.87	11.64	15.31	15.37	14.92	16.69	15.49	14.98	20.03	20.07	18.40
NOV	10.90	10.14	9.76	13.27	12.69	12.44	13.07	12.54	12.20	16.73	16.67	15.94
DEC	9.40	8.84	7.86	11.10	11.75	10.69	11.19	11.70	10.70	14.31	14.58	13.54

And the maximum value observed in May and June characterizes the relatively shortest distance between the sun and the earth and less aerosols. The greatest value (measured $\overline{H}_m$ = 25.21MJ/m^{2}day & estimate*d* $\overline{H}_{eNew}$ = 26.26 MJ/m^{2}day) was observed at Jumla (2300m above the sea level) and the minimum radiation valu (measured $\overline{H}_m$ = 7.49MJ/m^{2}day & estimated $\overline{H}_{eNew}$ = 7.42 MJ/m^{2}day) was observed at Biratnagar (72m above the sea level).

The result shows the altitude, aerosol and weather dependency of the radiation. The observed value of solar insolation for all sites is suitable for solar farming, agriculture and forestation. Fig. 1(a-d) is linear plot between measured & model estimated monthly mean daily solar radiations and months to compare the date. Figures 2-5 are the scatter plot between the measured and model estimated monthly mean daily global solar radiation for different sites to analyze the performance of new model. The plots and Table 2 show close agreement of the measured value with new model estimated values. It was found that solar insolation, depends on clearness index, vary with month of the year, weather condition of the sky and the location. The least value of solar insolation and statistical analysis for Kathmandu show the more attenuation of radiation due to the presence of aerosol/smokes in the sky of Kathmandu valley than other sites.

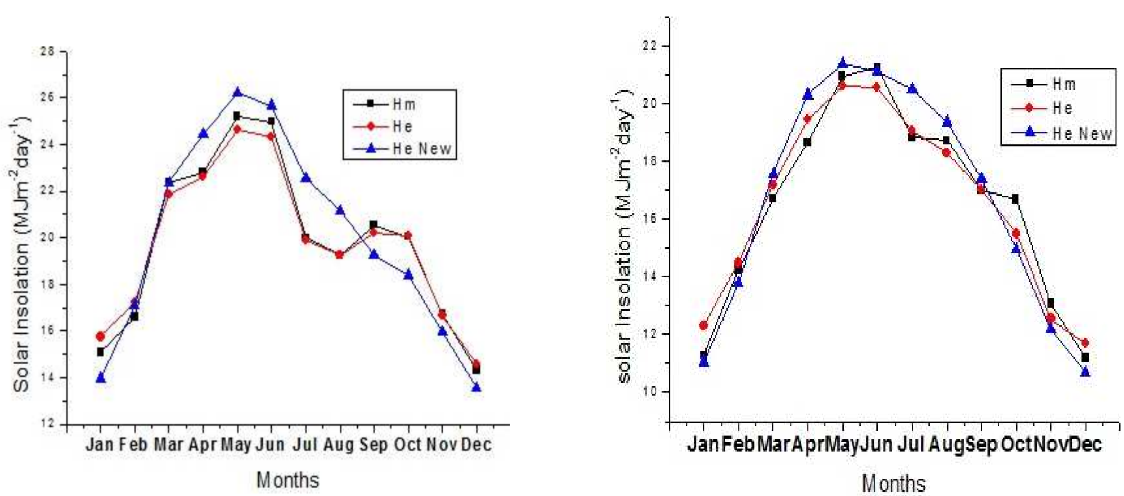

Figure 1: (c) Variation of radiation with months for Pokhara **(d)** Variation of radiation with months for Jumla

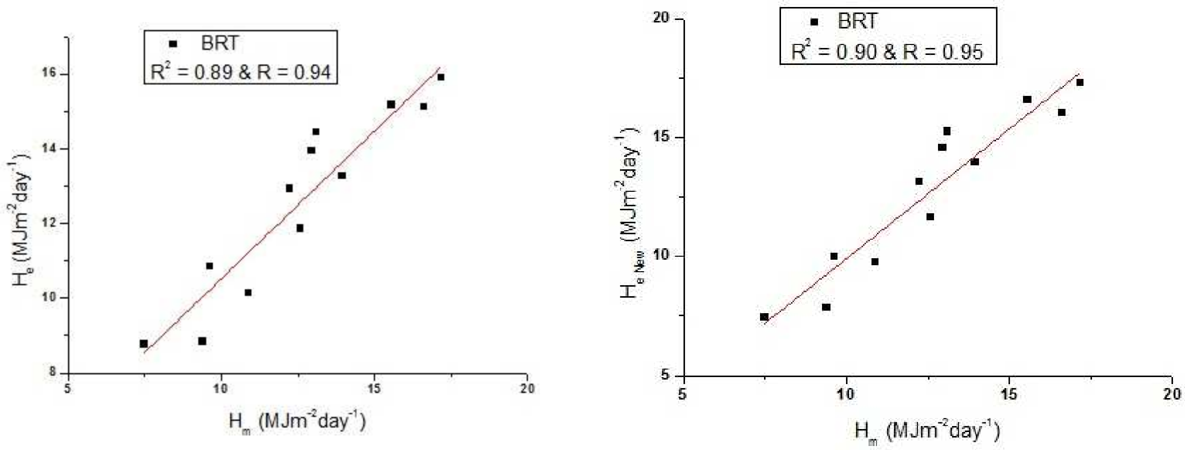

Figure 2: Measured ($\overline{H}_m$) versus Estimation global solar Radiation ($\overline{H}_e$) by Angstrom-Prescott model and New model for Biratnagar.

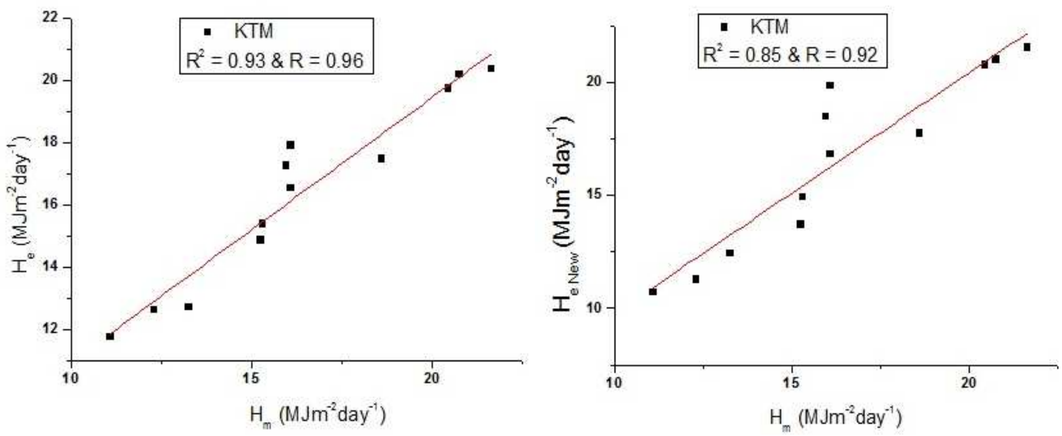

Figure 3: Measured ($\overline{H}_m$) versus Estimation global solar Radiation ($\overline{H}_e$) by Angstrom-Prescott model and New model for Kathmandu.

Table 2. Regression constants and errors analysis.

		Regression constants						**RMSE**	**MBE**	**MPE %**	**R^2**		**R**		**CC**
SN	**Location**	a*	b*	a**	b**	c**	d**	**New**	New	New	A-P	New	A-P	New	New
1	BRT	0.301	0.164	0.355	0.024	-0.00038	-0.0039	1.08	0.155	-0.68	0.89	0.90	0.94	0.95	0.95
2	KTM	0.364	0.280	0.677	0.025	-0.00062	-0.0046	1.49	0.20	-0.89	0.93	0.85	0.96	0.92	0.92
3	PKR	0.442	0.169	0.301	0.029	-0.00054	-0.0019	0.97	0.15	-0.33	0.96	0.95	0.98	0.98	0.97
4	JML	0.383	0.394	0.894	0.009	-0.00023	-0.0049	1.3	0.22	-0.65	0.99	0.92	0.99	0.96	0.95

Note: *Regression coefficients for Angstrom-Prescott model

** Regression coefficients for proposed new model & A-P stands for Angstrom-Prescott model.

Moreover, Table 2 presents the least values of root mean square error RMSE, mean bias error MBE and mean percentage error MPE, from statistical analysis, indicate the best linear regression relations to estimate global solar radiation at Biratnagar, Kathmandu, Pokhara and Jumla in Nepal.

The additional statistical indicators were also used to evaluate the accuracy and performance of new model. All sites have higher values of R & R^2 whereas the highest value of R is 0.98 (R^2 = 0.95) at Pokhara and minimum value of R is 0.92 (R^2 = 0.85) at Kathmandu, correlation coefficient CC observed 0.92 at Kathmandu, 0.95 at Biratnagar & Jumla and 0.97 at Pokhara. Figures from 1-5 of the plots of global solar radiations model estimated by the Angstrom-Prescott and new one also proved the higher performance of the new model in comparison to the value estimated in Ref. [5,19,23] and nearly same value as in Ref. [9,16,17].

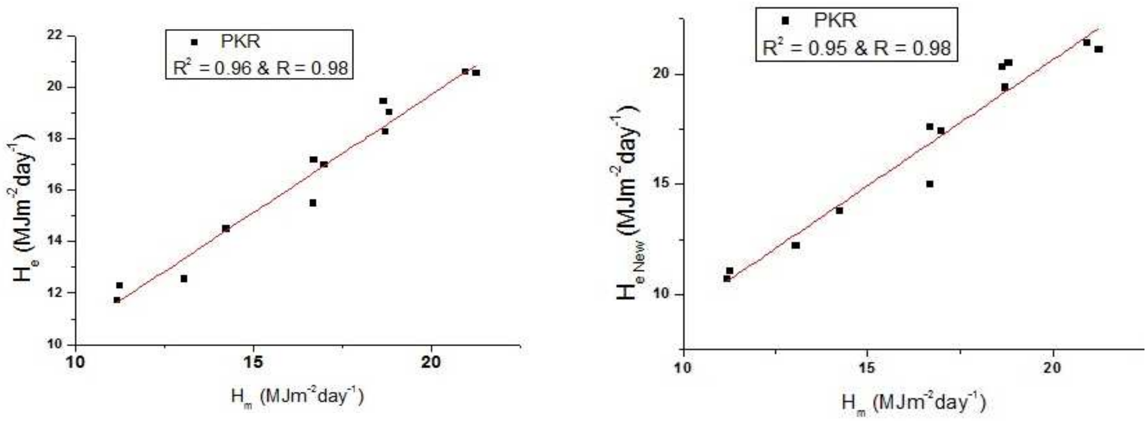

Figure 4: Measured vs Estimation global solar Radiation by Angstrom-Prescott model and New model for Pokhara.

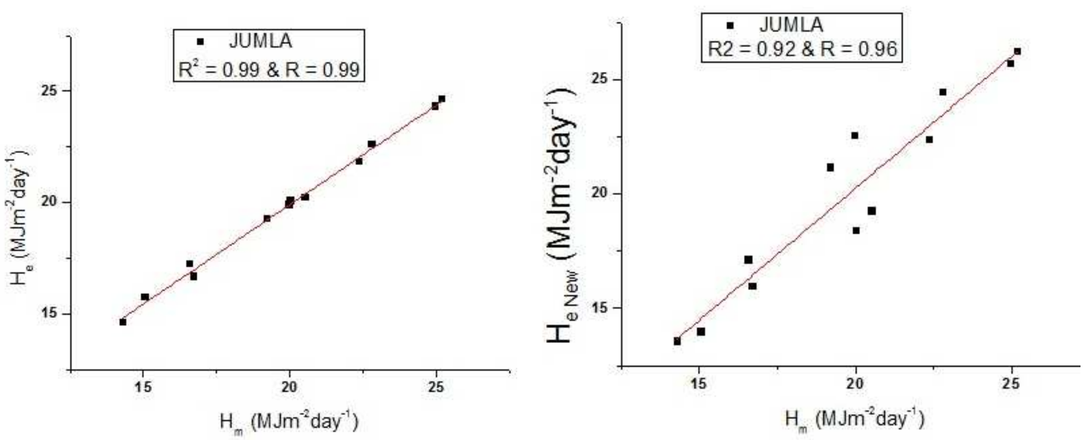

Figure 5: Measured ($\overline{H}_m$) versus Estimation global solar Radiation ($\overline{H}_e$) by Angstrom-Prescott model and New model for Jumla.

4. Conclusion

Solar radiation database of any site is essential for designing and sizing the solar energy systems for that particular locality and ultimately for the broader world community [18] for a sustainable future energy. Important finding of this work are as follows:

- Development of the linear regression equation *(an empirical model)* to estimate the global solar insolation based on *easily available meteorological parameters; temperature and relative humidity*. The model proved that higher the temperature more is the solar radiation but the effect of humidity is in opposite/reverse manner.

b. Admirable harmony has been found between measured and estimated global solar radiation by new model. The statistical analysis techniques also confirm the better performance of the model at four sites.
c. Measurements showed that west and high altitude regions in Nepal are the places where high potential of global solar radiation was observed and least value of radiation was observed in eastern part and low altitude locations. In general abundant solar radiation is observed at all sites in Nepal.
d. Ubiquitously available data can be used to developed model and hence to estimate daily and monthly mean daily solar radiation for the locations and the locations of similar geographical characteristics.

This study also *recommends* that Pokhara, Jumla and other places having similar geographical and meteorological parameters are suitable for the endeavor of the solar projects to resolve the energy deficiency in Nepal. The model is more useful and rational than the model proposed by Adhikari et al. [9].

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