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Estimation of the Direct Solar Radiation on Fixed and Tracking System in Algeria

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***Abstract*— In the present paper, the direct solar irradiance DNI is evaluated using the clear sky model for different locations in Algeria. The method is applied to estimate the hourly direct solar irradiance and the daily direct solar radiation at Ghardaia for two typical days and for different positions of the collector aperture: fixed horizontal and tilted apertures, single tracking apertures and two axis tracking apertures. To compare solar resources in Algeria, the monthly mean daily direct solar radiation and the annual mean daily direct solar radiation for six different locations, i.e., Algiers, Annaba, Oran, Ghardaia, Bechar and Tamanrasset, corresponding to different climatic regions are also estimated**

***Keywords*— Hottel model; direct solar radiation; direct irradiance; tilted aperture; tracking aperture.**

I. INTRODUCTION

A reasonably accurate knowledge of the solar radiation is necessary for solar energy applications such as solar thermal and photovoltaic applications. Estimating the directt normal solar irradiance (DNI) is of great importance in the development of concentrating solar power plant technologies. The DNI allows the identification of the most suitable sites available for deploying the concentrating solar power plants.The analysis of a solar energy system design is typically initiated by predicting its performance over a "typical" "clear" day. There are a number of clear-day mathematical solar irradiance models that may be used to predict the expected maximum hour-by-hour direct solar irradiance. Hottel [1976] presented a model, with good accuracy and simple use, to estimate the clear-day transmittance of direct solar radiation through clear sky. Hottel's clear-day model of direct normal solar irradiance is based on atmospheric transmittance calculations for four different climate zones in the globe using the 1962 U.S. Standard Atmosphere (e.g. [1], [2]). Using Hottel's model for different tracking systems and orientations, the purpose of the actual work is to estimate the direct solar irradiance available to collectors in Algeria.

II. DIRECT APPERTURE IRRADIANCE

For concentrating solar collector, the solar designer is only interested in the direct irradiance on the aperture. The collector aperture irradiance, the rate at which solar energy is incident on the aperture per unit aperture area, may be calculated form the direct normal irradiance *Ibn* and the angle of incidence *i* using the relation (e.g. [3] – [7]):

$$Iba = Ibn.\cos(\theta_i) \quad (1)$$

A. Direct normal solar irradiance

Hottel (1976) has presented a method for estimating the beam radiation Ibn (W/m^2) transmitted through clear atmospheres which takes into account zenith angle and altitude for a standard atmosphere and four climate types (e.g. [4] – [7]):

$$Ibn = I_0.\tau b \quad (2)$$

I_0 is the extraterrestrial solar irradiance, outside the earth's atmosphere measured on the plane normal to the irradiance on the Nth day of the year. It is given by the following relation (e.g. [03]-[05]):

$$I_0 = Isc.\left[1 + 0{,}034.\cos\left(\frac{360.N}{365.25}\right)\right] \quad (3)$$

I_{sc} is the solar constant and its value is taken as 1367 W/m^2; τb is the atmosphere transmittance of beam radiation. τb is given by Kreithand and Kreider in the form (e.g. [4] – [8]):

$$\tau b = a_0 + a_1.\exp\left(-k/\cos\theta_z\right) \quad (4)$$

The constant ao, a1 and k for the standard atmosphere with 23 km visibility are given for altitudes less than 2.5 km by Hottel:

$$a_0^* = 0{,}4237 - 0{,}00821(6 - Al)^2$$
$$a_1^* = 0{,}5055 - 0{,}005958(6{,}5 - Al)^2 \quad (5)$$
$$k^* = 0{,}2711 - 0{,}01858(2{,}5 - Al)^2$$

Where:

$$a_0 = a_0^*.r_0; \quad a_1 = a_1^*.r_1; \quad k = k^*.r_k$$

The correction factors r_0, r_1 and r_k are given for climate types in table I by Hottel

TABLE I
CORRECTION FACTORS FOR CLIMATE TYPES (e.g. [4]-[8])

Climate type	r_0	r_1	r_k
Tropical	0,95	0,98	1,02
Mid latitude summer	0,97	0,99	1,02
Subarctic summer	0,99	0,99	1,01
Mid latitude winter	1,03	1,01	1,00

θ_z is the solar zenith angle, (deg)
φ is the latitude angle, expressed in degree, of the location (positive in the North of the Equator and negative in the South);
δ is the declination angle, calculated using the equation of Cooper 1969 (e.g. [9] –[11]):

$$\delta = 23{,}45.\sin\left[360.\frac{284 + N}{365}\right] \quad (6)$$

B. Angle of incidence

In the design of solar energy systems, it is most important to be able to predict the angle between the sun's rays and a vector normal (perpendicular) to the aperture or surface of the collector. This angle is called the angle of incidence. We present the equations to calculate the angle of incidence for fixed- axis, single axis tracking and also both tow-axis (full) tracking apertures (e.g. [9]-[14]).

1. Fixed apertures (no- tracking)

The expression of the angle of incidence in term of the orientation of the collector and the solar altitude and azimuth angles is given by:

$$\theta_i = \cos^{-1}(\sin\alpha.\cos\beta + \cos\alpha.\sin\beta.\cos(\gamma - A)) \quad (7)$$

α: solar altitude angle, (deg);

β: aperture tilt angle from the horizon, (deg) :

γ : tilt angle of the aperture axe from the North, (deg) ;

A: solar azimuth angle, (deg).

The expression (7) will be simplified according to the following cases:

a- For tilted aperture facing south: (γ=180°)

$$\theta_i = \cos^{-1}(\sin\alpha.\cos\beta - \cos\alpha.\sin\beta.\cos A) \quad (8)$$

b- For horizontal apertures: (β=0°)

$$\theta_i = \cos^{-1}(\sin\alpha) \quad (9)$$

c- For vertical apertures: (β=90°)

$$\theta_i = \cos^{-1}(\cos\alpha.\cos(\gamma - A)) \quad (10)$$

2. Tracking apertures

Some types of concentrating collector are designed to operate with tracking rotation about only one or tow axis. The other important angle for the tracking apertures is the tracking angle measures rotation about the tracking axis ρ.

Single-axis tracking apertures

Here a tracking drive system rotates the collector about an axis of rotation until the sun central ray and the aperture normal are coplanar. We present the equations for the angle of incidence and the tracking angle, first for cases where the tracking axis is arbitrarily oriented but still parallel to the surface of the earth, and then for cases where the tracking axis is inclined relative to the surface of the earth (e.g. [9]-[14]).

a- Horizontal tracking axis oriented in North- South:

$$\rho = \tan^{-1}(\sin A/\tan\alpha) \quad (11)$$
$$\theta_i = \cos^{-1}\left(1 - (\cos\alpha)^2.(\cos A)^2\right)^{0,5} \quad (12)$$

ρ: tracking angle, (deg)

b- Horizontal tracking axis oriented in East-West:

$$\rho = \tan^{-1}(-\cos A / \tan\alpha) \quad (13)$$

$$\theta_i = \cos^{-1}\left(1-(\cos\alpha)^2.(\cos A)^2\right)^{0,5} \quad (14)$$

c- Tilted tracking axis toward the south at the local latitude angle:

The tracking angle and the incidence angle are equal to:

$$\rho = \omega \qquad \theta_i = \delta \quad (15)$$

ω: hour angle, (deg)

Two-axis tracking apertures

With two-axis tracking, a collector aperture will always be normal to the sun:

$$\cos\theta_i = 1 \quad (16)$$

Two types of tracking mechanism are commonly in use for this purpose: azimuth / elevation tracking systems (also called az-el systems) and polar or equatorial tracking systems (e.g. [2]-[17]):

III. DIRECT SOLAR RADIATION ENERGY INCIDENT ON A COLLECTOR APERTURE

The daily aperture solar radiation energy is the irradiance on the aperture summed over a full day from sunrise to sunset (e.g. [5]-[18]):

$$H_{ba} = \int_{tl}^{tc} I_{ba}.dt \quad (17)$$

H_{ba} is the daily direct aperture solar radiation energy, (J/m^2); and t_l and t_c respectively the sunrise time and the sunset time expressed in hours.

To predict the time of sunrise and sunset and the length of day, we can use the solar altitude angle. If the local horizon is flat, the solar altitude is zero at sunrise and sunset. The hour angle at sunrise and sunset becomes (e.g. [3]-[10]):

$$\omega_s = \cos^{-1}(-\tan\delta.\tan\phi) \quad (18)$$

With:
ω_s: hour angle at sunset, (deg)

Sunrise time and sunset time are given by equations:

$$tsr = 12 - \frac{\omega_s}{15} \quad (19)$$

$$tst = 12 + \frac{\omega_s}{15} \quad (20)$$

The hours of daylight may be calculated as [10]:

$$S_0 = \frac{2.\omega_s}{15} \quad (21)$$

S_0: hours of daylight at day, (h)

By using the Trapeze method for second order, the equation (17) to calculate the daily beam aperture solar energy becomes:

$$Hba = h\sum_{i=1}^{S_0-1} Iba_{sr+ih} \quad (22)$$

With :

h : integration step is one hour, (3600 sec)
Iba_{sr+ih} : Direct aperture Irradiance in the step (sr+ih), (W/m^2)

IV. RESULTS AND DISCUSSION

A computer program in FORTRAN, based on the above method, has been developed. The input data required are the day, the location, and the orientation of the collector and whether the collector is fixed or tracking the sun about one or two axes. Since it doesn't change rapidly, the declination angle may be calculated only once a day. Hourly calculations are then carried out for the hour angle and the sun's altitude and azimuth. These values are used in the appropriate equation for the angle of incidence and the tracking angle. Aperture irradiance is calculated once per hour and stored in an array. The irradiance is then summed over the day through application of linear averaging between hours to give the daily aperture solar radiation energy.

Figure 1 through Figure 4 show the results of such a study carried out for the location of Ghardaia (latitude +32,48°- longitude +3,66°- Altitude 500m). Figure 1 and Figure 3 represent a typical summer clear day and Figure 2 and Figure 4 represent a clear day of winter

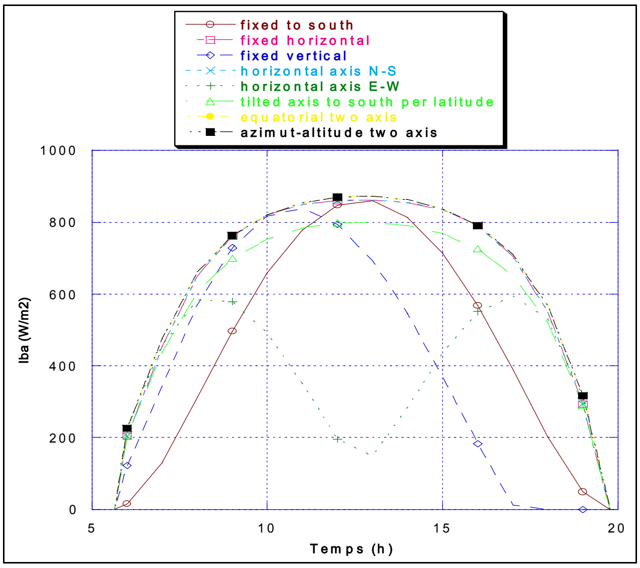

Fig. 1. Clear-day aperture irradiance for different fixed and tracking aperture configurations for Ghardaia on June 22.

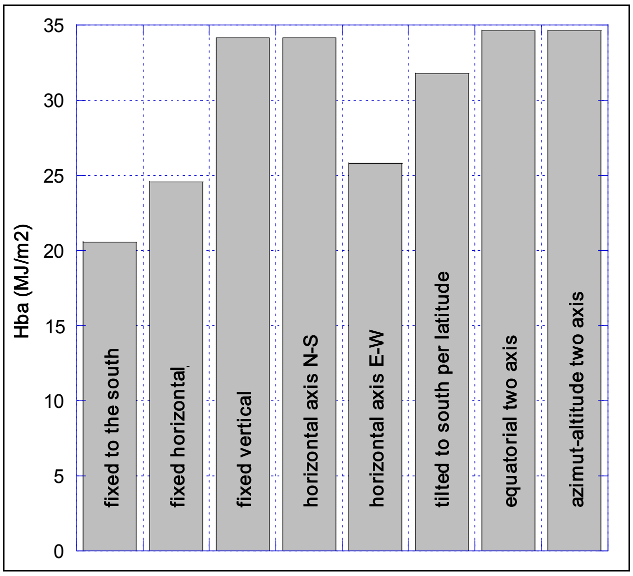

Fig. 3. Clear-day direct solar radiation energy for different fixed and tracking aperture configurations for Ghardaia on June 22.

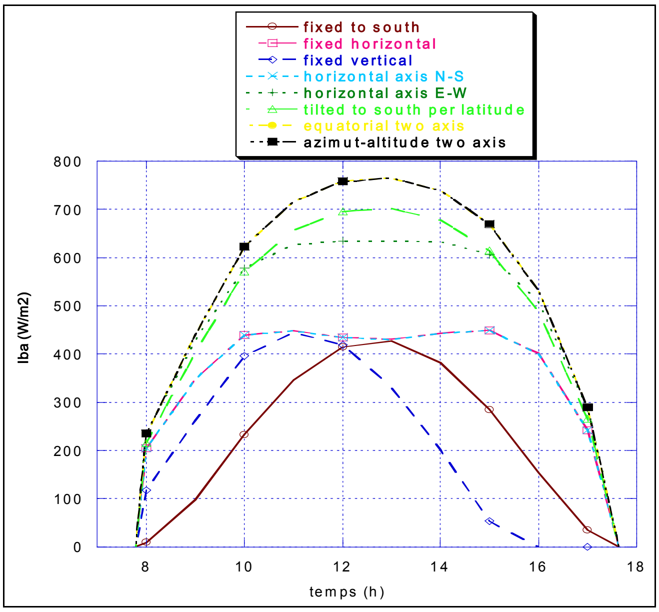

Fig. 2. Clear-day aperture irradiance for different fixed and tracking aperture configurations for Ghardaia on December 22.

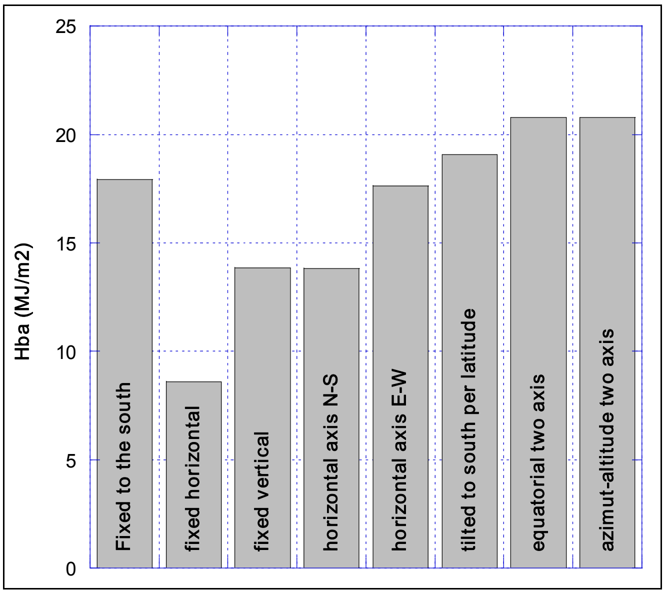

Fig. 4. Clear-day direct solar radiation energy for different fixed and tracking aperture configurations for Ghardaia on December 22.

The maximum amount of the direct solar radiation is collected when a collector aperture points directly towards the sun, therefore the angle of incidence is equal to zero this occurs in the case of two-axis tracking. Figure 1 shows that in

Ghardaia in the summer, if the single axis of tracking is oriented in the north/south (N/S) direction, the reduction in beam aperture irradiance from the two-axis tracking case is minimal. As can be seen in Figure 3, the difference between the day's solar radiation energy on a N/S-oriented single-axis-tracking aperture and on a two-axis tracking aperture is only about 1 percent. If the single tracking axis is oriented in the east-west (E/W) direction, the amount of beam solar energy entering the aperture of the E/W single-axis tracker is only 76 percent of the energy that could have been collected if the cosine effect had been zero all day.

In the winter, as shown in Figure 2, the reverse is true. The performance of the E/W oriented single axis tracked aperture approaches that of the two-axis tracked aperture even in the morning and afternoon. In fact, the E/W tracking aperture receives 84 percent of the maximum amount of energy, whereas the N/S-oriented single-axis tracking aperture receives only 64 percent of the maximum solar energy for that day. Taken over the entire year, the N/S-oriented single-axis-tracking aperture receives slightly more energy than does the E/W axis aperture. However, the variation of the daily irradiance over the year is much greater for the N/S axis orientation than for the E/W orientation.

The beam aperture irradiance for fixed-aperture collectors is also shown on Figures 1 and Figure 2 for summer and winter in Ghardaia. A fixed horizontal surface receives more aperture solar radiation energy over the day than does a latitude-tilted and south-facing surface in the summer. In the winter, however, the horizontal fixed surface in Ghardaia receives only 49 percent of the daily energy that a latitude-tilted surface does.

In Figure 5 we estimate the Annual Monthly Mean Daily direct solar radiation for two-axis tracking aperture in clear typical day at six typical locations in Algeria: Algiers located in the North of Algeria, Annaba located in the extreme East of the Algerian North, Oran located in northwestern Mediterranean coast of Algeria, Béchar located in the northwestern limit of the Algerian Sahara (Saoura), Ghardaia located in the northern Algerian Sahara and Tamanrasset located in the extreme South of Algeria. These locations correspond to different climatic regions in Algeria. In Table II, the geographical positions and the type of climate for each location are reported.

TABLE II
LATITUDE ANGLE, LONGITUDE ANGLE, ALTITUDE FROM MEAN SEA LEVEL, AND CLIMATE TYPE FOR DIFFERENT LOCATION

Climate type	Altitude (km)	Longitude (°)	Latitude (°)	Location
Mid latitude summer	0,025	3,15	36,43	Algiers
Mid latitude summer	0,040	7,8	36,8	Annaba
Mid latitude summer	0,099	-0,37	35,38	Oran
Tropical	0,806	-2,15	31,38	Bechar
Tropical	0,500	3,66	32,48	Ghardaia
Tropical	1,378	5,31	22,47	Tamanrasset

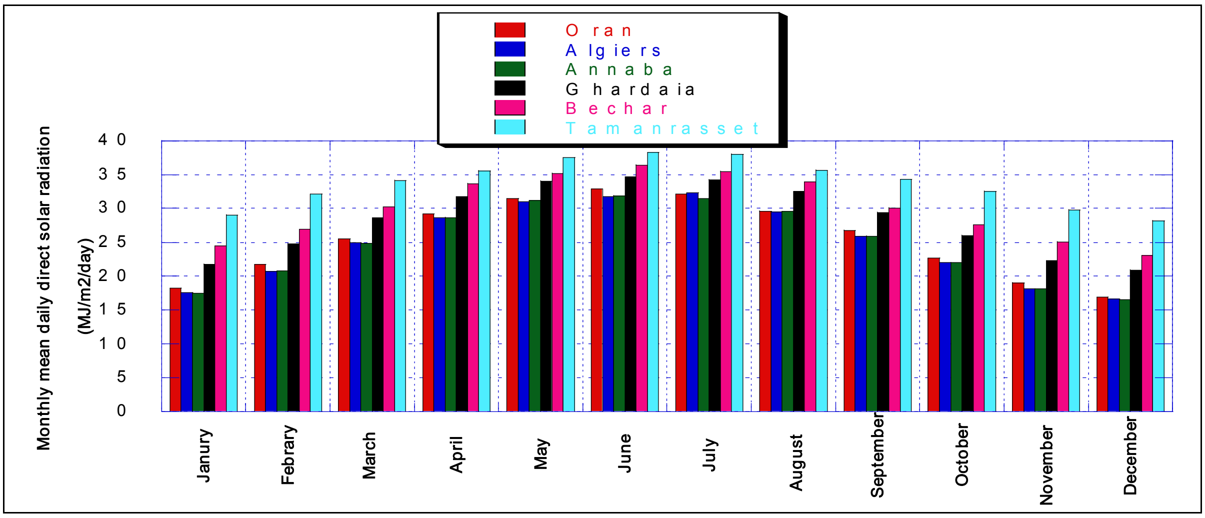

Fig.5. Annual monthly mean daily direct solar radiation for two-axis tracking aperture for different locations in Algeria.

The most important direct solar radiation potential is found in the Sahara for Ghardaia, Béchar and the best in Tamanrasset. The annual monthly mean direct solar radiation varies for Oran, Algiers and Annaba between 16 MJ/m^2/day and 32 MJ/m^2/day, for Bechar between 23 MJ/m^2/day and 37 MJ/m^2/day, Ghardaia between 20 MJ/m^2/day and 35 MJ/m^2/day and Tamanrasset between 28 MJ/m^2/day and 38 MJ/m^2/day,The peak of direct solar radiation occurs in the cases of Algiers in July with 32,25 MJ/m^2/day, Annaba in June with 31,85 MJ/m^2/day, Oran in June with 32,83 MJ/m^2/day, Béchar in June with 36,37 MJ/m^2/day, Ghardaia in June with 34,61 MJ/m^2/day and Tamanrasset in June with 38,24 MJ/m^2/day.

CONCLUSION

A model, based on the clear sky, has been used to estimate the direct solar radiation at different locations representative of different climatic conditions in Algeria. Direct Normal Irradiance (DNI) is used to estimate the potential for concentrating solar collectors. The model incorporates various geographical and meteorological factors. The values of the monthly mean daily direct solar irradiation for the six selected locations have been estimated. The values of hourly direct solar irradiation for Ghardaia have also been estimated. In this study, we show that the clear sky model can be used to estimate the direct solar radiation in Algeria. This work is important for the prediction of the monthly mean daily direct solar radiation over any selected city in Algeria. Knowledge of the solar radiation enables us to derive information about the performance of solar energy systems with many applications in estimating the direct solar radiation for the cities studied and possibly elsewhere with similar climatic conditions. Results show that DNI is very important. It is more than sufficient for the solar thermal exploitation of solar energy. This more particularly true in the south.

REFERENCES

[1] T. Markvart, *Solar electricity.* 2nd ed. New York: John Wiley and Sons Inc.; 1996.

[2] A. Hossein Mousazadeh, A. Alireza Keyhani, B. Arzhang Javadi, A. Hossein Mobli, C. Karen Abrinia, B. Ahmad Sharifi. A review of principle and sun-tracking methods for maximizing solar systems output. *Renewable and Sustainable Energy Reviews* 13; 2009, 1800–1818.

[3] M. Iqbal, An introduction to solar radiation. Canada: *Academic Press.* ISBN 0-12-373752-4; 1983.

[4] J. A. Duffie, W. A. Beckman, *Solar engineering Transmittance of thermal processes.* 2nd ed. Madison: John Wiley &Sons, Inc.; 1991.

[5] H. C. Hottel, A simple model for estimating the transmittance of direct solar radiation through clear atmospheres. *Solar Energy,* Vol. 18, USA; 1976, pp. 129-134

[6] İnci TÜRK TOĞRUL, Estimation of solar radiation from angstroms coefficients by using geographical and meteorological data in Bishkek, Kyrgyzstan. Isı Bilimi ve Tekniği Dergisi, *J. of Thermal Science and Technology,* 29, 2; 2009, 99-108.

[7] Maria Eugênia Vieira da Silva, Alex Sandro de Araújo, and Marcelo Ricardo Queiroz Medeiros. Adjustment of the Clear Sky Coefficients for the Transmission of Solar Radiation under the Ambient Conditions in Fortaleza. *RIO 02 - World Climate & Energy Event.* January 6-11; 2002.

[8] PI. Cooper, The absorption of solar radiation in solar stills. *Solar Energy* 12(3): 1969, 313–31.

[9] J. C. Zimmerman, Sun pointing programs and their accuracy. *Sandia National Laboratories Report* SAND81-0761; September 1981.

[10] Mehmet Yorukoglu, Ali Naci Celik, A critical review on the estimation of daily global solar radiation from sunshine duration. *Energy Conversion and Management* 47; 2006, 2441–2450

[11] G. Notton , P. Poggi, Cristofari C. Predicting hourly solar irradiations on inclined surfaces based on the horizontal measurements: Performances of the association of well-known mathematical models. *Energy Conversion and Management* 47; 2006, 1816–1829

[12] K. K. Chong, C. W. Wong, General formula for on-axis sun-tracking system and its application in improving tracking accuracy of solar collector. *Solar Energy* 83; 2009, 298–305.

[13] L. O. Lamm, A New Analytic Expression for the Equation of Time. *Solar Energy* 26 (5); 1981, 465.

[14] J. K. Linn, J. C. Zimmerman, A Method for calculating shadows cast by two-axis tracking solar collectors. Report SAND79-0190, *Sandia National Laboratories,* Albuquerque NM; November 1979.

[15] M. Alata, M. A. Al-Nimr , Y. Qaroush, Developing a multipurpose sun tracking system using fuzzy control. *Energy Conversion and Management* 46; 2005, 1229–1245

[16] C. George Bakos, Design and construction of a two-axis Sun tracking system for parabolic trough collector (PTC) efficiency improvement. *Renewable Energy* 31; 2006, 2411–2421.

[17] H. R. Ghosh, N. C. Bhowmik, M. Hussain, Determining seasonal optimum tilt angles, solar radiations on variously oriented, single and double axis tracking surfaces at Dhaka. *Renewable Energy,* 2009, 1–6.

[18] K. Nalin, Gautam and N. D. Kaushika, A Model for the Estimation of Global Solar Radiation Using Fuzzy Random Variables. *Centre for Energy Studies, Indian Institute of Technology, Delhi, India* American Meteorological Society; 2002.