Model based Optimization of Tilt angle for Solar PV Panels in Jodhpur

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ABSTRACT
The performance of a photovoltaic (PV) panel is primarily dependent on the solar radiation received. Thus the position and angle of tilt of a PV panel are important factors in PV system design. The amount of energy captured from the sun depends on the tilt angle of the solar panels. If solar panels are mounted horizontally or vertically, lesser energy is captured than if the panels face due south in the Northern Hemisphere and due north in the Southern Hemisphere and are tilted towards the sun. This paper examines the factors affecting tilt angle for the solar panel and aims to select an appropriate theoretical model for determining the optimal tilt angle for solar PV panels placed at Jodhpur, Rajasthan. Four isotropic models and four anisotropic models have been considered to identify the best model for the given conditions. The selected model has been validated by applying it for finding out the yearly optimum tilt angle for Jodhpur and comparing the results with those obtained from the data collected at the solar panels installed at IIT Rajasthan. It is found that Liu and Jordan model gives results which are quite close to the results of the data measured at the solar panel installed at IIT Rajasthan. This model is also used for determination of monthly average and seasonal average of optimal tilt angle. It has been concluded that the average optimum tilt angle at Jodhpur for winter months is 47.6^0 and for summer months 12^0. Further, in the monthly adjusted system, the loss of energy is less than 1% (0.97) if the angle of tilt is adjusted seasonally. It is hence suggested that seasonally adjusted tilt angle should be preferred. However, yearly average fixed tilt can be used in many general applications (e.g. domestic water heating) in order to keep the manufacturing and installation costs of collectors low. The loss in collected radiation for the yearly average fixed angle is around 12.7% as compared with the optimum tilt at Jodhpur. Hence, for attaining higher efficiency, the collector should be designed such that the angle of tilt can easily be changed at least on a seasonal basis, if not monthly.

General Terms
Estimation of solar radiation, Optimization of tilt angle.

Keywords
Tilt angle, solar panel, diffused radiation models.

1. INTRODUCTION
Three of the main renewable energy resources are solar energy, geothermal energy and tidal energy. The solar energy emerges from fusion reaction of four hydrogen nuclei into one helium nucleus [1].The intensity of solar radiation absorbed at earth's surface mainly depends upon (a) insolation at earth's surface and (b) properties of earth's surface.Various factors which affect the output of a complete solar PV system depend upon the factors affecting the output a single solar cell and a solar panel as well. Different parameters such as cell temperature, energy conversion efficiency and the maximum power point tracking affect the output of a single solar cell [2]. The factors which mainly affect the output of a solar panel are shading, orientation and tilt angle of the solar panel.A shadow falling on a cell reduces the total output by:

[1] Reducing the energy input to the cell, and
[2] Increasing energy losses in the shaded cell.

Orientation of the PV array is one of the more important aspects of the site assessment. Facing the PV array due South is ideal, but slight deviations can be permitted. For example, an unshaded PV array with a tilt of 35^0 and facing +/- 45^0 away from due South (SE or SW) will still receive 92% of the annual solar radiation as compared to the PV array facing due south[1].

Solar radiation is measured in the form of global and diffuse radiation on a horizontal surface [3].Solar panels are positioned at an angle to the horizontal to increase the amount of radiation falling on the panel so the optimum tilt angle should be calculated which than determines the solar conversion efficiency. Optimum tilt can be determined by using bi-axial tracking system. Tracking system is mainly classified into two: viz., Manual and Automatic [3]. Manual systems are usually employed to fix the tilt angle of the panel at a particular angle defined by the latitude of the location. However, model based determination of optimum tilt angle has emerged as a popular method of operating the solar system inthe recent years. These angles are implemented in both manual and automatic tracking systems. The following two methods can be used in order to achieve optimum tilt:

a) Monthly optimization
b) Seasonal optimization

Automatic tracking systems are expensive and need energy (usually a part of solar energy is used) for their operation.Further, they cannot be applied and maintained easily [4]. The techniques proposed by researchers for calculating optimum tilt angle are usually based on:

a) Geographic factor(Rb),
b) Clearness index (Kt) and
c) Declination angle(δ).

Through experimental analysis it is proven that the geographic factor method of estimating the optimum tilt angle is the best method for finding the optimum tilt angle of solar panels at a location [5]. This paper utilizes the geographic factor method for estimating the daily beam radiation on tilted surfaces.

1.1 Estimation of total solar radiation on inclined surface
Monthly-average of daily total radiation on a tilted surface (H_T) can be calculated by calculating the direct beam (H_B), diffuse (H_S) and reflected components (H_R) of the radiation. Thus the

incident total radiation on tilted surface is given by the equation [3]:

$$H_T = H_B + H_S + H_R \tag{1}$$

1.1.1 Estimation of Daily Beam Radiation (H_B)

The expression for the daily beam radiation received by a tilted solar collector is:

$$H_B = (H - H_d)R_b \tag{2}$$

where H and H_d are the monthly-average daily global and diffuse radiation component for the horizontal surface, and R_b is the ratio of average daily beam radiation on a tilted surface to that on a horizontal surface [3].

Liu and Jordan (1962) have suggested that R_b can be estimated by assuming that there is no atmosphere. In the northern hemisphere the surfaces which are sloped towards the equator, R_b is given as[6]:

$$R_b = \frac{\cos(\emptyset-\beta)\cos\delta\sin\omega_s'+\omega_s'\sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega_s+\omega_s\sin\emptyset\sin\delta} \tag{3}$$

here

$$\omega_s' = min\{cos^{-1}(-\tan\emptyset\tan\delta), cos^{-1}(-\tan(\emptyset-\beta)tan\delta)\} \tag{4}$$

hereω_s is the sunset hour angle. ‘‘min’’ is the smallest of the two terms. In the southern hemisphere the surfaces which are sloped towards the equator, R_b is given as below:

$$R_b = \frac{\cos(\emptyset+\beta)\cos\delta\sin\omega_s'+\omega_s'\sin(\emptyset+\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega_s+\omega_s\sin\emptyset\sin\delta} \tag{5}$$

here

$$\omega_s' = min\{cos^{-1}(-\tan\emptyset\tan\delta), cos^{-1}(-\tan(\emptyset+\beta)tan\delta)\} \tag{6}$$

here Φ is the latitude, δ is the declination angle and ω is the angle from the local solar noon. The declination angle is given as [7]:

$$\delta = 23.45sin[360(284+n)/365] \tag{7}$$

here n is the n^{th} day of the year (1-365).

1.1.2 Estimation of Ground Reflection Radiation (H_R)

The ground reflected radiation can be given after assuming the reflection as isotropic. Hence the daily ground reflected radiation can be expressed as

$$H_R = H\rho(1-\cos\beta)/2 \tag{8}$$

here H is the monthly-average daily global radiation on a horizontal surface, β is optimum tilt angle, ρ is surface reflectivity assumed as a constant and the value is 0.2.

1.1.3 Estimation of Sky Diffused Radiation (H_S)

Diffuse irradiance are defined as the solar radiation which are coming from the sky dome except from the direct radiation from sun and the circumsolar region (three degrees of the sun). Sky diffused radiations are difficult to measure because for measuring sky diffuse radiation the pyranometer should be shaded so that it could not receive direct radiation and radiation from the circumsolar region [8].

Isotropic and anisotropic models are used to determine the ratio of diffuse solar radiation on a tilted surface to that of a horizontal surface. The isotropic models assume that the diffuse sky radiations are uniformly distributed over the sky dome. Hence, the diffuse radiation is dependent on the portion of the sky dome which can be seen by the collector. The anisotropic models assume that diffuse sky radiations are collection of anisotropically distributed diffused radiation component in the circumsolar region (sky near the solar disc) plus and isotropically distributed diffuse component from the rest of the sky dome [3].

The sky-diffuse radiation can be expressed as

$$H_S = R_d H_D \tag{9}$$

Here R_d is the ratio of the average daily diffuse radiation on a tilted surface to that on a horizontal surface.The diffuse radiation models chosen for study are as follows:

1.1.3.1 Isotropic Models

The isotropic models assume that the diffuse sky radiations are uniformly distributed over the sky dome. Hence, the diffuse radiation is dependent on the portion of the sky dome which can be seen by the collector.

(a) Liu and Jordan model (1962)[6]

$$R_d = \frac{1}{2}(1+\cos\beta) \tag{10}$$

Here H_d is the intensity of diffuse radiation onto a horizontal plane [W/m2].

(b) Koronakis model (1986)[10]

$$R_d = \frac{1}{3}(2+cos\,\beta) \tag{11}$$

(c) Tian*et al.* model (2001)[11]

$$R_d = 1-\beta/180 \tag{12}$$

(d) Badescu model (2002)[12]

$$R_d = \big(3+cos(2\beta)\big)/4. \tag{13}$$

1.1.3.2. Anisotropic Models

The anisotropic models assume that diffuse sky radiations are collection of anisotropically distributed diffused radiation component in the circumsolar region (sky near the solar disc) plus and isotropically distributed diffuse component from the rest of the sky dome [3].

(a) Hay and Davies model (1979)[9]

$$R_d = \frac{H_b}{H_o}R_b + \left(1-\frac{H_b}{H_o}\right)[(1+\cos\beta)/2] \tag{14}$$

(b) Steven and Unsworth model (1980)[13]

$$R_d = 0.51R_b + \{(1+cos\beta)/2\} - \frac{1.74}{1.26\pi}\left[sin\beta - \left(\beta.\frac{\pi}{180}\right)cos\beta - \pi sin^2(\beta/2)\right] \tag{15}$$

(c) Skartveit and Olseth model (1986)[14]

Then diffuse radiation onto an inclined plane is expressed by:

$$R_d = \frac{H_b}{H_o}R_b + \Omega\cos\beta + \left(1-\frac{H_b}{H_o}-\Omega\right)(1+\cos\beta)/2 \tag{16}$$

$$\begin{Bmatrix} \Omega = 0.3 - 2F_{Hay} for F_{Hay} < 0.15 \\ \Omega = 0 for F_{Hay} \geq 0.15 \end{Bmatrix} \tag{17}$$

here $F_{Hay} = \frac{H_b}{H_o}$.

(d) Reindl*et al.* model (1990)[15]

$$R_d = \frac{H_b}{H_o}R_b + \left(1 - \frac{H_b}{H_o}\right)[(1+\cos\beta)/2][1 + \sqrt{H_b/H}\,sin^3(\beta/2)] \quad (18)$$

After substituting the values of H_S, H_B and H_R in eq. 1 the total solar radiation on a tilted surface can be expressed as:

$$H_T = (H - H_d)R_b + H\rho(1-\cos\beta)/2 + H_dR_d \quad (19)$$

This equation will be used for determining the optimum tilt angle, while substituting the value of R_d for the various models described in eq.(10) to eq.(18) respectively.

2. METHODOLOGY

Here the theoretical aspect of selecting appropriate tilt angle for the solar panel and selecting an appropriate model for determining the optimal tilt angle for solar PV panels to be placed at Jodhpur has been examined. The selected model has been validated by applying it for finding out the yearly optimum tilt angle for Jodhpur and comparing the results with those obtained from the data collected at the solar panels installed at IIT, Jodhpur.

Computer programs in MS Excel have been developed using the mathematical models to calculate the optimum tilt angle and to calculate monthly, seasonally and yearly average daily total radiation for the tilt angles in between 0 to 90^0. Also separate computer programs have been developed for examine the effect of different isotropic and anisotropic diffused radiation models on total radiation on tilted surface monthly, seasonally and yearly. Graphs were plotted between the total irradiations (MJ/m^2.day) versus tilt angle(between 0^0 to 90^0) for each month for the latitude of interest. Thus optimum tilt angle was computed for each month for Jodhpur. Also, the results obtained for Jodhpur station (over the period of one year from May 2012 to April 2013) have been compared with data collected at the solar panels installed at IIT, Jodhpur where the PV panels are fixed and positioned at annual optimum tilt towards the equator (south facing).

3. EXPERIMENTAL DATA

The experimental data used in this study are the field data of solar radiation from 2002 to 2011 available at the National Renewable Energy Laboratory (NREL) website.[16] This data has been obtained by using a thermoelectric pyranometer, which is calibrated once a year with reference to the World Radiometric Reference (WRR). However, some of the critical information such as calibration of meter,change in instrument, data quality control process, and shading effect is not considered for these stations. Therefore it is expected that some data sites may possibly introduce errors in the results. But the overall error remains small, as the errors are negligible here because the data is averaged over a period of ten years.

4. RESULTS AND DISCUSSION

The monthly average of daily global radiation for a given month is calculated by using the following equation:

$$\bar{H} = \sum_{j=1}^{NY}\left[\left(\sum_{i=1}^{ND} H_{i,j}\right)/ND\right]/NY \quad (20)$$

where$\bar{H}$ = monthly average of daily global radiation

$H_{i,j}$ = daily global radiation
ND = Total number of days in the month
NY = Total number of year of data
i = index representing a day
j = index representing a year

The total solar radiation falling on tilted surface was computed for tilt angles 0, 10, 20, 30,40, 50, 60, 70, 80 and 90 degrees for each month of the year for Jodhpur using the various models by using MS Excel spread sheet with embedded program in Microsoft Visual Basic for Applications. Also, optimum tilt angle was computed for each month and for Jodhpur. Then by using MS Excel graphics software package, graphs were plotted between the total insolationand tilt angle for each month in Jodhpur. The solar reflectivity (ρ) was assumed to be 0.2 [3].

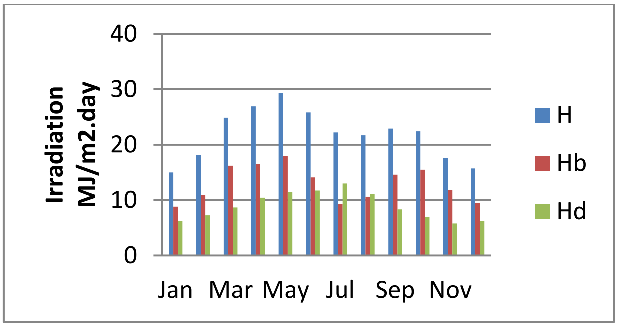

Fig.1 Monthly average of daily global radiation (H), beam radiation (Hb) and diffuse radiation (Hd) on a horizontal surface in Jodhpur.

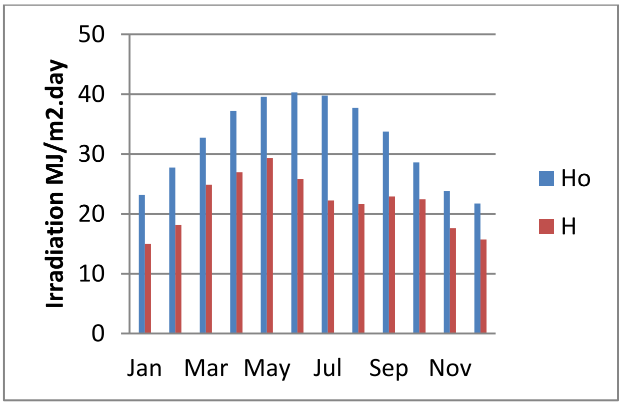

Fig.2 Monthly average of daily global radiation (H) and monthly average of extra-terrestrial daily radiation (Ho) on a horizontal surface in Jodhpur

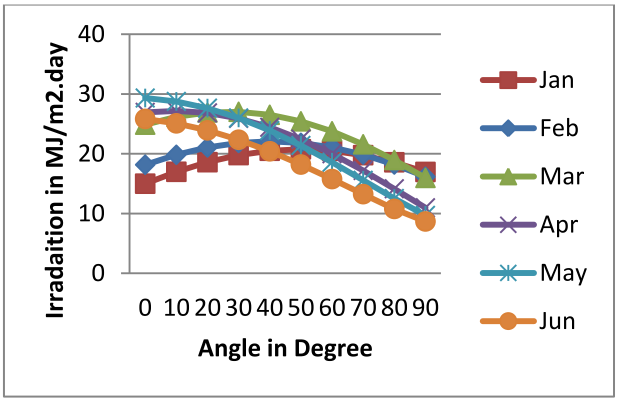

Fig.3(a)Monthly average of daily total solar radiation on a south facing panel in Jodhpur for the months of January-June.

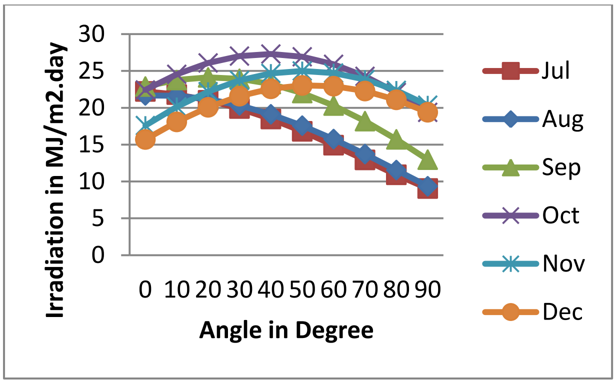

Fig.3 (b).Monthly average of daily total solar radiation on a south facing panel in Jodhpur for the months of July-December.

Table 1 gives a comparison of β_{opt} for each month of the year at Jodhpur obtained from the mathematical model given in eq.19.

Table 1. Estimated Solar Radiation at Optimum Tilt Angle (βopt) for Each Month of the Year for a South Facing Solar Collector at Jodhpur

Month	βopt (in degree)	Monthly Radiation (Ht)(MJ/m^2. month)	Daily Radiation(Ht)(MJ/m^2. day)
Jan	49.80	642.89	20.74
Feb	40.20	617.77	22.06
Mar	27	838.35	27.04
Apr	9	815.33	27.18
May	0	908.96	29.32
Jun	0	774.73	25.82
Jul	0	688.83	22.22
Aug	3.60	673.03	21.71
Sep	21.60	723.95	24.13
Oct	39.00	846.31	27.30
Nov	50.40	750.07	25.00
Dec	52.80	714.84	23.06

The optimum angle of tilt of the flat-plate collector in January is substituted as $49.8^0$and the total monthly solar radiation collected at this tilt is estimated as 642.89 MJ/m^2. The optimum tilt angle in May, June and July is zero degree and the monthly solar radiation at this angle is 908 MJ/m^2, 775 MJ/m^2 and 689 MJ/m^2 respectively. The optimum tilt angle increases during the winter months and reaches a maximum of 52.8^0in December which collects 714 MJ/m^{2}of solar energy monthly.

The model results are validated by comparing them with the estimated data available from the standard software PV Watts [17] which is commonly used by field practitioners. This software can be freely downloaded from the NREL website [16]. The comparative analysis is shown in Table 2.

Table 2. Comparison of Daily PV Radiation estimates obtained by PV Watts Calculator and the mathematical model for fixed Solar Collector at Jodhpur

Mon-th	Estimate from PV Watts calculator (Optimum tilt: 26.50)	Estimate from Mathe-matical model (Optimum tilt: 31.80)	Difference in solar radiation (MJ/ m2.day) (c= b-a)	Per degree sensitivity of solar radiation (d= c/(31.80-26.50))
	Solar Radiation (MJ/m2.day) (a)	Solar Radiation (MJ/ m2.day) (b)		
Jan	19.82	20.74	0.92	0.17
Feb	21.83	22.06	0.24	0.04
Mar	23.74	27.04	3.30	0.62
Apr	24.59	27.18	2.58	0.49
May	23.95	29.32	5.37	1.01
Jun	21.35	25.82	4.47	0.84
Jul	17.60	22.22	4.62	0.87
Aug	18.40	21.71	3.31	0.62
Sep	22.60	24.13	1.54	0.29
Oct	24.57	27.30	2.73	0.51
Nov	20.69	25.00	4.31	0.81
Dec	19.03	23.06	4.02	0.76

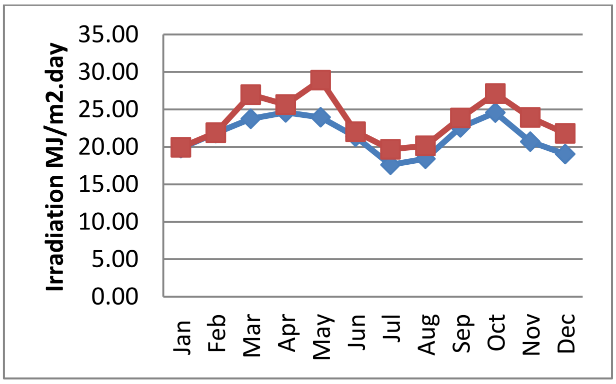

Fig. 4 Comparison of Daily PV radiation obtained by PV Watts Calculator and the mathematical model for a South Facing Solar Collector at Jodhpur

The model results are further validated by comparing the model results with the data measured at solar plant at IIT, Jodhpur over the period of one year from May 2012 to April 2013 as shown in Table 3.

Table 3.Comparison of Daily PV Radiation data measured at IIT, Jodhpur and the estimate from the model for a South Facing Solar Collector at Jodhpur

Month	Data from IIT, Jodhpur (Tilt: 33^0)	Data from Mathematical model (Optimum tilt: 31.8^0)	Difference in solar radiation (MJ/ m^2.day) (c= b-a)	Per degree sensit-ivity of solar radiation (d= c/(31.8-26.5))
	Solar Radiation (MJ/m^2.day)(a)	Solar Radiation (MJ/ m^2.day)(b)		
Jan	15.75	20.74	4.99	1.56
Feb	18.14	22.06	3.93	1.23
Mar	20.21	27.04	6.83	2.13
Apr	18.23	27.18	8.95	2.80
May	21.10	29.32	8.22	2.57
Jun	18.06	25.82	7.76	2.42
Jul	17.62	22.22	4.60	1.44
Aug	15.62	21.71	6.09	1.90
Sep	17.37	24.13	6.76	2.11
Oct	19.78	27.30	7.52	2.35
Nov	16.42	25.00	8.58	2.68
Dec	15.42	23.06	7.64	2.39

An attempt is hence made in the next subsection to identify the best model for the given conditions out of the various isotropic and anisotropic models described in section II. Four isotropic models described in eq.(10), (11),(12),(13) respectively and four anisotropic models described in eq. (14), (15), (16), (18) respectively considered for this purpose.

Table 4 represents monthly average of daily total radiation for different isotropic diffused radiation models. With the panel tilted at an angle proposed by the Badescu model [12] collects maximum monthly average of daily total radiation but the results obtained by Liu and Jordan model are quite close to the results of the data measured at the solar panel installed at IIT, Jodhpur.

Table 4. Estimated Daily Total Radiation obtained by employing different Isotropic Diffused Radiation Models at Jodhpur

Mon-th	Badescu model (2002)		Tian et al. model (2001)		Koronakis model (1986)		Liu and Jordan model	
	Optimum Tilt	Total Radiation Ht (MJ/m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)
Jan	31.8	19.94	31.8	13.16	31.8	14.94	31.8	**19.54**
Feb	31.8	21.89	31.8	13.95	31.8	16.04	31.8	**21.43**
Mar	31.8	26.97	31.8	17.46	31.8	19.96	31.8	**26.41**
Apr	31.8	25.65	31.8	14.22	31.8	17.22	31.8	**24.98**
May	31.8	25.65	31.8	13.13	31.8	16.42	31.8	**24.92**
Jun	31.8	22.01	31.8	9.15	31.8	12.53	31.8	**21.26**
Jul	31.8	19.67	31.8	5.43	31.8	9.17	31.8	**18.84**
Aug	31.8	20.14	31.8	8.00	31.8	11.19	31.8	**19.43**
Sep	31.8	23.85	31.8	14.74	31.8	17.14	31.8	**23.32**
Oct	31.8	27.12	31.8	19.51	31.8	21.51	31.8	**26.67**
Nov	31.8	23.93	31.8	17.60	31.8	19.26	31.8	**23.56**
Dec	31.8	21.80	31.8	14.95	31.8	16.75	31.8	**21.40**

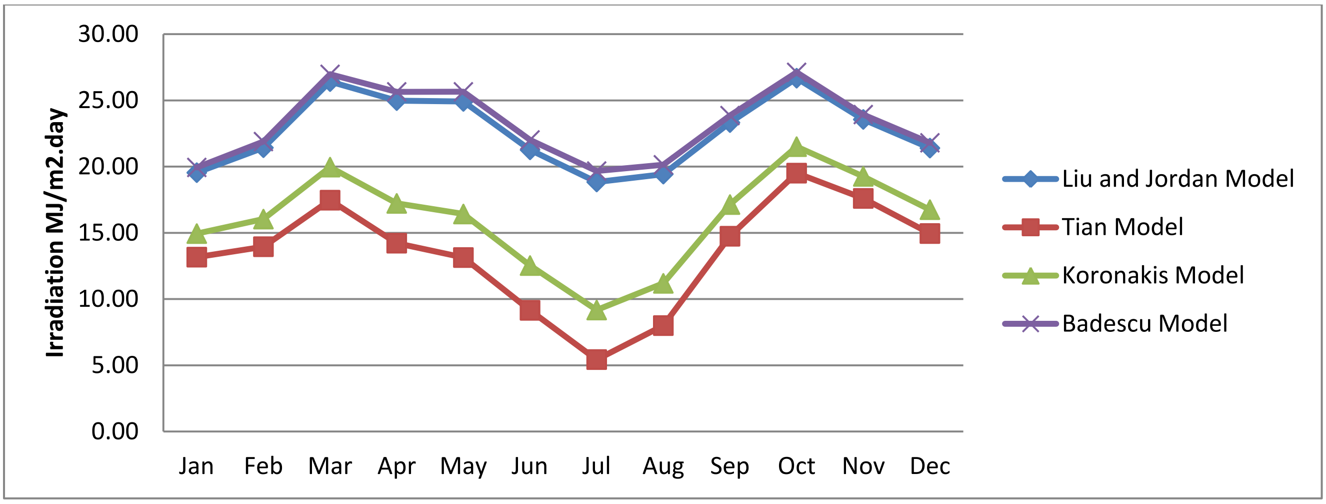

Fig. 5 Daily Total Radiation obtained by different Isotropic Diffused Radiation Models at Jodhpur

Table 5.Estimated Daily Total Radiation obtained by employing different Anisotropic Diffused Radiation Models at Jodhpur

Reindl et al. model (1990)		**Skartveit and Olseth model (1986)**		**Steven and Unsworth model (1980)**		**Hay model (1979)**	
Optimum Tilt	Total Radiation Ht (MJ/m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)	Optimum Tilt	Total Radiation Ht (MJ/ m^2.day)
31.8	23.82	31.8	22.91	31.8	25.44	31.8	23.37
31.8	25.31	31.8	23.97	31.8	27.51	31.8	24.52
31.8	29.63	31.8	28.36	31.8	32.73	31.8	29.01
31.8	28.02	31.8	25.77	31.8	31.5	31.8	26.55
31.8	27.47	31.8	24.94	31.8	31.32	31.8	25.8
31.8	24.65	31.8	21.19	31.8	27.52	31.8	22.07
31.8	24.03	31.8	19.18	31.8	25.95	31.8	20.16
31.8	23.73	31.8	20.05	31.8	26.11	31.8	20.88
31.8	26.34	31.8	24.68	31.8	29.11	31.8	25.31
31.8	29.96	31.8	29.46	31.8	32.32	31.8	29.98
31.8	27.49	31.8	27.19	31.8	28.95	31.8	27.63
31.8	26.25	31.8	25.75	31.8	27.61	31.8	26.22

Table 5 represents monthly average of daily total radiation for different anisotropic diffused radiation models. With the panel tilted at an angle proposed by the Steven and Unsworth anisotropic model [13] collects maximum monthly average of daily total radiation but the results obtained by Skartveit and Olseth model [14] are quite close to the results of the data measured at the solar panel installed at IIT, Jodhpur so this can be selected as best anisotropic model. The results can be easily interpreted graphically as shown in Fig. 6.

Fig. 6 shows that all the anisotropic models show a similar trend in variation and their estimates are quite similar in non-cloudy months but there is significant difference in the months with the cloud cover i.e. May to September. Although, the Steven and Unsworth model [13] gives maximum radiation but the results obtained by Skartveit and Olseth model [14] are quite close to theresults of the data measured at the solar panel installed at IIT, Jodhpur so this can be selected as best anisotropic model which gives best results for the cloudy day and when the sky is not clear.

5. CONCLUSION

From the results obtained it is found that Liu and Jordan model gives results which are quite close to the results of the data measured at the solar panel installed at IIT Rajasthan. This model is used for determination of monthly average and seasonal average of optimal tilt angle. It has been concluded that the average optimum tilt angle at Jodhpur for winter months is 47.6^0 and for summer months 12^0.

Table 6 represents a summary of optimum tilt, seasonally adjusted tilt and yearly average tilt and monthly solar radiation on a tilted south facing plane at Jodhpur. It can be concluded from the table that in the monthly adjusted system, the loss of energy is less than 1% (0.97) if the angle of tilt is adjusted seasonally.It is hence suggested that seasonally adjusted tilt angle should be preferred. However, yearly average fixed tilt can be used in many general applications (e.g. domestic water heating) in order to keep the manufacturing and installation costs of collectors low. The loss in collected radiation for the yearly average fixed angle is around 12.7% as compared with the optimum tilt at Jodhpur.

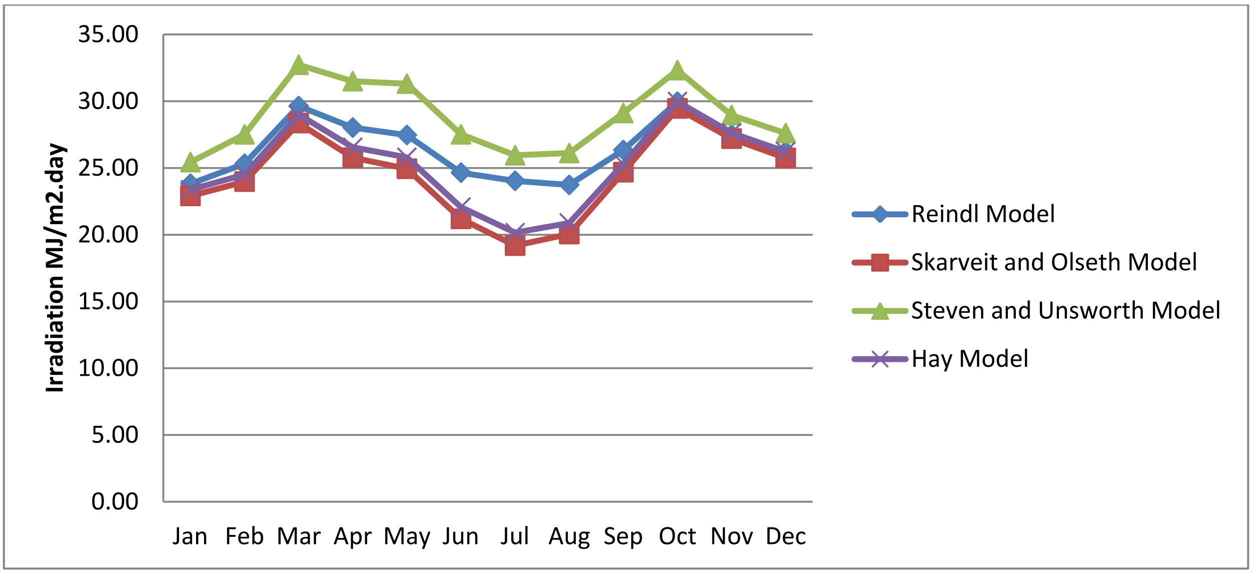

Fig. 6 Daily Total Radiation obtained by different Anisotropic Diffused Radiation Models at Jodhpur

Table 6. Optimum Tilt, Seasonally Adjusted Tilt and Yearly Average Tilt and Monthly Solar Radiation on a Tilted South Facing Plane at Jodhpur.

Month	Monthly optimum tilt	Monthly Radiation (Ht) (MJ/ m^2. month)	Seasonally adjusted tilt (β)	Monthly Radiation (Ht) (MJ/ m^2. month)	Yearly optimum tilt (β) (Latitude)	Monthly Radiation (Ht) (MJ/ m^2. month)	Yearly optimum tilt (β)	Monthly Radiation (Ht) (MJ/ m^2. month)
Jan	49.80	642.89	52.80	642.26	26.5	614.40	31.80	618.04
Feb	40.20	617.77	27.00	605.62	26.5	611.11	31.80	612.87
Mar	27	838.35	27.00	838.35	26.5	736.06	31.80	836.01
Apr	9	815.33	27.00	785.96	26.5	737.85	31.80	769.37
May	0	908.96	0.00	908.96	26.5	742.42	31.80	896.04
Jun	0	774.73	0.00	774.73	26.5	640.49	31.80	660.41
Jul	0	688.83	0.00	688.83	26.5	545.63	31.80	609.69
Aug	3.60	673.03	26.40	641.07	26.5	570.55	31.80	624.30
Sep	21.60	723.95	26.40	722.09	26.5	677.89	31.80	715.57
Oct	39.00	846.31	26.40	829.47	26.5	761.81	31.80	840.62
Nov	50.40	750.07	52.80	749.58	26.5	620.75	31.80	717.83
Dec	52.80	714.84	52.80	714.84	26.5	590.08	31.80	675.68
		8995.06		8901.76		7849.02		8576.42

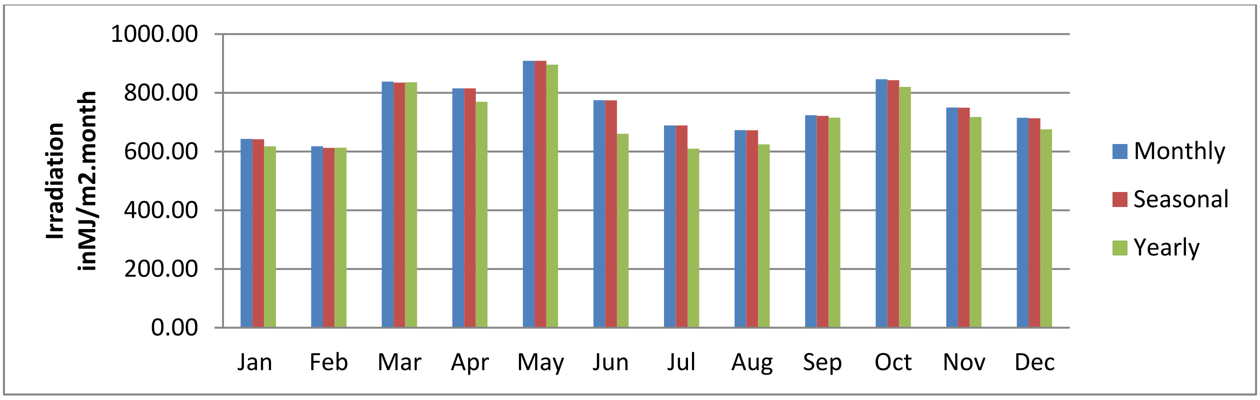

Fig. 7 Optimum Tilt, Seasonally Adjusted Tilt and Yearly Average Tilt and Monthly Solar Radiation on a Tilted South Facing Plane at Jodhpur

Fig. 7 represents monthly solar radiation on a tilted surface at Jodhpur at optimum tilt, seasonally adjusted tilt and yearly average tilt. The figure reveals that during the month of Feb. and Mar.the estimated solar radiation is almost samefor monthly, seasonal and yearly average tilt, but in other months the estimated radiation is quite low in comparison to the monthly and seasonal tilt. Hence, for attaining higher efficiency, the collector should be designed such that the angle of tilt can easily be changed at least on a seasonal basis, if not monthly.

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