Comparison of Seventeen Models to Estimate Diffused Solar Radiations on a Tilted Surface

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Abstract

This study aims to evaluate daily diffused solar irradiance from a horizontal to a tilted surface using 17 different sky models based on a variety of different sky conditions. The selected sky models are classified into two categories namely isotropic and anisotropic, based on assumptions made to define behavior of diffused radiations all over sky dome. Solar radiations falling on a tilted surface are computed and compared for two stations Lahore and Khuzdar based on their respective clearness indices. Solar radiation data for period of one year (Jan 2016 – Dec 2016), was used to evaluate the sky models. The daily surface albedo was computed from hourly albedo from MERRA-2 to estimate reflected component of radiations. The calculations were based on daily measured global irradiance for horizontal surface. Beam, diffused and reflected components of radiation on the tilted surface were computed with tilt angle variation from 0° to 90°. The maximum mean annual radiations for Khuzdar with the highest sky clearness index (K_T) and Lahore with lowest K_T among selected stations were found to be 326 W/m^2 and 209 W/m^2 respectively. The daily optimum tilt angle corresponding to the maximum annual radiations varies from 0 to 75° throughout the year. The respective average maximum total solar radiation for optimum annual tilt is 190 W/m^2 and 289 W/m^2 for Lahore and Khuzdar respectively. A comparison of different models shows almost 6 to 11% increase in mean monthly total radiations with monthly optimum tilt as compared to latitude tilt for both Lahore and Khuzdar.

Keywords: Optimal tilt angle, Solar radiations, Isotropic models, Anisotropic models

1. Introduction

Renewable energy has evolved as a global fast-growing trend to fulfill increasing energy demands around the globe due to its environment friendly nature and sustainable production of energy. A variety of renewable energy resources (Solar, Wind, Geothermal etc.) are being used as an alternative to non-sustainable resources like coal. However, a substantial increase in the use of solar energy has made it the fastest growing energy source among all other renewable energy resources. Solar energy is standing out as an important integrated energy source to meet the current energy needs partly due to its easy deployment on both smaller and larger scales (Li et al., 2015). Solar energy is being utilized through both active (direct conversion of solar energy to electrical energy) and passive (indirect use of solar energy for water heating, cooking, etc.) technologies. Solar PVs, flat plate collectors, and concentrated solar panels are a few examples of modern active solar conversion technologies used these days. However, the lower efficiency of solar energy conversion devices is one of the major concerns associated with the commercial application of these devices. The design of such devices requires the optimal installation parameters to enhance their performance.

The performance of solar energy conversion devices is a function of surface orientation with respect to the sun; the azimuth angle (γ) and the surface inclination or tilt angle (β). Hence, both the orientation and tilt of the solar PV quantify the amount of solar radiations falling on an inclined surface of a panel (Kaddoura et al., 2016). The solar PVs are often installed as a fixed unit with a certain amount of tilt while the sun covers a unique path as the day passes. The application of solar tracking system is the best possible way to maximize the incident solar radiations by adjusting the position of solar PV to face the sun path throughout the day. A Single Axis Solar Tracking (SAST) system can achieve up to 18% higher solar energy compared to a fixed collector (Batayneh et al., 2019). While, an increase of about 13-15% in the daily power output of PV arrays is observed with the application of a dual-axis tracking system (Şenpinar and Cebeci, 2012). However, the hefty costs of the solar tracking systems put a limitation to its application especially for the smaller scale systems. The amount of global radiations falling on the Earth surface varies with the climatic conditions,

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seasonal changes and latitude of a location affecting the performance of solar PV modules (Huld et al., 2012). A reasonable increase in the performance of solar PV modules can be achieved by using an optimal monthly, seasonally and annual tilt angle. Khoranizadeh et al. (Khorasanizadeh et al., 2014) reported an effective 22% and 23% increment in the harnessed energy by using optimal tilt of solar PV on seasonal and monthly basis. While, 14% energy enhancement can be achieved by adjusting the Solar PV on semi-yearly basis.

The data for global and diffused solar radiations are measured on a horizontal surface. The conversion of available radiation data for the horizontal surface to the tilted surface is a prerequisite to estimate the required optimal tilt angle (Demain et al., 2013)The total solar radiations (H_T) reaching the Earth is composed of three major components; beam or direct radiations (H_B), diffused (H_D), and reflected radiations (H_R). Diffused radiations get scattered due to the presence of aerosols or clouds in the atmosphere. While, the reflected radiation is the component of total radiations which is reflected through different surfaces (Drummond, 1956). The approximation of total tilted radiation is the sum of tilted beam, reflected, and diffused radiations which are calculated separately. The estimation of beam component on tilted surface is often simple as it involves geometric relation (R_b) which represents the ratio of beam radiations between the tilted and horizontal surface (Huld et al., 2012). For the diffused part of the radiation, availability of the measured data for different locations is difficult to estimate, as the diffused component is a complex function of humidity, turbidity, clearness index, sky condition, humidity, and many other atmospheric and meteorological conditions in addition to the geometric factor (Duffie and Beckman, 1980)

Several different models have been presented by different researchers to estimate the diffused component on tilted surface. The formulations of these models are based on the sunshine hours, sky clearness index (K_T), relative humidity (R_h), and other meteorological factors (Jamil et al., 2017). These models based on their unique method to address the diffused radiations, are classified as the isotropic and anisotropic models. Isotropic models present simplified methodology to estimate the diffused radiations by assuming the isotropic scattering of radiations throughout the sky dome. While, the anisotropic models include detailed insights considering both isotropic and anisotropic parts of the diffused radiations. Reindl et al. (Reindl et al., 1990) proposed studied a set of 28 significant factors and selected four significant factors after reduction to present his model the model was based isotropic (all over the sky dome) and anisotropic (around the Sun disc and horizon) part of the diffused radiations. Noorian et. al. (Noorian et al., 2008) compared the performance of twelve different isotropic and anisotropic models for the evaluation of diffused radiation data on tilted surface. The chosen twelve models were examined for the west and south facing irradiances at Karaj (35°55′N; 50°56′E) Iran. The methodology used by all these models was almost same for the estimation for beam and reflected component whereas different techniques were suggested for the estimation of diffused component.

This study presents the evaluation of isotropic and anisotropic sky models to maximize the solar radiations. The chosen isotropic models include Liu and Jordan Model (LJ), Koronakis Model (Kr), Bdescu Model (Ba) and Tian Model (Ti). While anisotropic models include Skarvieth and Olseth model (SO), Wilmott model (Wi), Perez Model (Pr), Hay Model (Ha), Steven and Unsworth Model (SU), Ma Iqbal Model (Iq), Reindl Model (Re), Bugler Model (Bu), Muneer Model (Mu), Klucher Model (Kl), Ma Iqbal Modified Model (IM), Temps Coulson Model (TC) and Gueymard Model (Gu). These sky diffuse models are used in estimation of diffuse component of radiations on tilted surface by varying the tilt angle from 0 to 90°. The models that estimates the maximum amount of solar radiations on tilted surface is recommended for the given latitude.

2. Solar Radiations Data

The measured solar radiations data for the present analysis was obtained through the Energy Sector and Management Assistance Program (ESMAP) of the World Bank. The data of Global Horizontal Irradiance (H_g), Beam irradiance (H_b), Diffused horizontal irradiance (H_d), for the stations Lahore and Khuzdar were used for the period of one year (January 1, 2016 – December 31, 2016). The data of H_g, H_b, and H_d for Lahore and Khuzdar were measured through the Tier 2 system equipped with CSP services Twin-Sensor Rotating Shadow-band Irradiometer (RSI). Measurement of ambient temperature and relative humidity was carried out through Campbell Scientific CS 215. Pre-calibration of RSI sensor against a high precision instrument, for two months, was carried out by German Aerospace Center (DLR) at Plataforma Solar de Almeria (PSA) (Kraas et al., 2015). The observed annual sum uncertainty for measurement of H_g, H_b, and H_d was reported to be less than 2 %. While the uncertainty associated with instantaneous measurement of H_g, H_d and H_b was less than 4%, 6%, and

4 % respectively using CSPS RSI (Services, 2019). The daily and weekly cleaning of irradiance sensors for Tier 2 systems along with the semi-yearly inspection was also performed by a local partner of ESMAP. The daily data retrieval was done by CSP services via GPS data transmission (Stökler et al., 2016). The data quality check was carried out in accordance with the guidelines given by Baseline Surface Radiation Network (BSRN) (Li et al., 2010). Three data quality checks were applied to remove outliers in the measured data. The first quality check was based on the minimum and maximum Physical Possible Limits (PPL) as given in equations (1a) and (1b). Where, G_{sc} represents the solar constant having a value of 1367W/m^{2}and G_e is the distance between the Sun and the Earth. The second data check involved the implementation of Extremely Rare Limits (ERL) for which the minimum and maximum values are given in equations (1c) and (1d). A third quality check was based on the comparison ratio of measured H_g and H_d data was performed across the dataset as given in equations (1e) and (1f). The data quality check was applied for the 10 minutes of data temporal resolution. The data set qualifying all of the mentioned quality checks were considered for the analysis to measure the daily mean values of global and diffused radiations while the rest of data was flagged. The period of day measuring the H_b above 120W/m^2 was marked as sunshine duration (Gueymard, 1993) as per the guidelines of World Meteorological Organization (WMO) to estimate the daily sunshine duration from measured H_b

$$H_g > -4\ W/m^2 \quad \text{(eq. 1a)}$$

$$H_g < 1.5\left(\frac{G_{sc}}{G_e}\right)((cos\ \theta_z)^{1.2}) + 100 \quad \text{(eq. 1b)}$$

$$H_g > -2\ W/m^2 \quad \text{(eq. 1c)}$$

$$H_g < 1.2\left(\frac{G_{sc}}{G_e}\right)((cos\ \theta_z)^{1.2}) + 50 \quad \text{(eq. 1d)}$$

$$\frac{H_d}{H_g} < 1.05 \qquad H_g > 50\ W/m^2,\ \theta_{sza} < 75° \quad \text{(eq. 1e)}$$

$$\frac{H_d}{H_g} < 1.1 \qquad H_g > 50\ W/m^2,\ 75° < \theta_{sza} < 93 \quad \text{(eq. 1f)}$$

Qasim et. al. (Qasim et al., 2014) suggested the classification of Pakistan's regions into five different zones (A to E) based on climatic conditions and geographical characteristics. These zones are classified based on K_T. This represents the ratio of H_g to H_o. Based on the ranges of cloud clearness index, the cloud conditions are classified into three categories: $0.65 < K_T \leq 1$ for clear sky condition, $0.3 < {}_TK_T \leq 0.65$ for partial cloud cover, and cloudy sky for $0 < K_T \leq 0.3$. The present study focuses on the analysis of two stations selected from different zones. Lahore with a clearness index value (K_T) of 0.49, belongs to zone B depicting intermediate sky conditions while Khuzdar having a clearness index (K_T) of 0.68 belongs to Zone C having clear sky conditions. The meteorological and geographical details for the selected stations are shown in Tab. 1.

Tab.1. Meteorological and Geographical Details of the Selected Stations

Stations	Station Code	Zone	Latitude	Longitude	H_g	H_d	N	T	R_H	K_T	K_D
			°N	°E	Wm^{-2}	Wm^{-2}	(hours)	°C	(%)		
Lahore	LHE	B	31.694	74.244	180	93	7.2	24.8	71.1	0.49	0.57
Khuzdar	KHZ	C	27.8178	66.6294	250	82	9.4	23.8	30	0.68	0.33

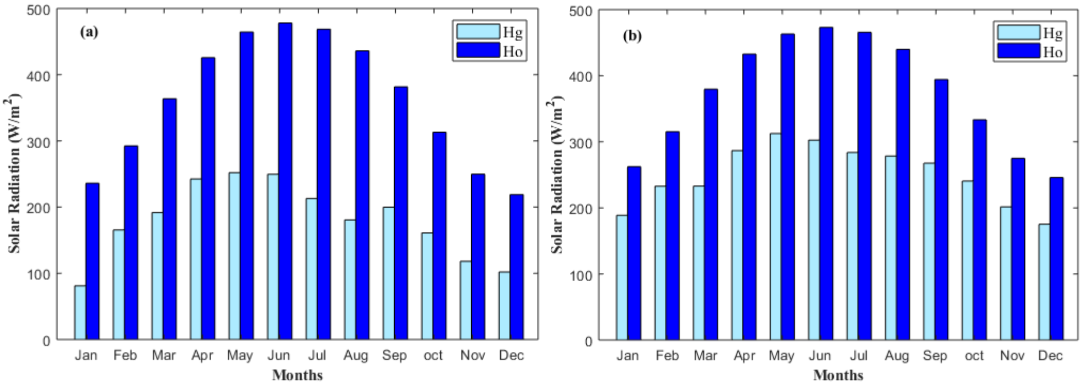

Fig. 1. Monthly Average Daily Global Horizontal and Extraterrestrial Radiations for (a) Lahore (b) Khuzdar

In Pakistan, May, June, and July are marked as the hottest months during the summer season with the longest sunshine. As the global irradiance depends upon the sunshine duration and the prevailing temperature of the region, the highest values of global irradiance for the site of Lahore and Khuzdar is observed during the months of May and June respectively as shown in Fig. 1. A slight decline for the month of July was observed as the duration of sunshine comparatively becomes shorter. The peak value of H_g is 252.1057W/m^2 for Lahore and 312.4451W/m^{2}for Khuzdar correspond to the month of May. The minimum values of global irradiance correspond to the months of November and December due to comparatively fewer sunshine hours and lower atmospheric temperature.

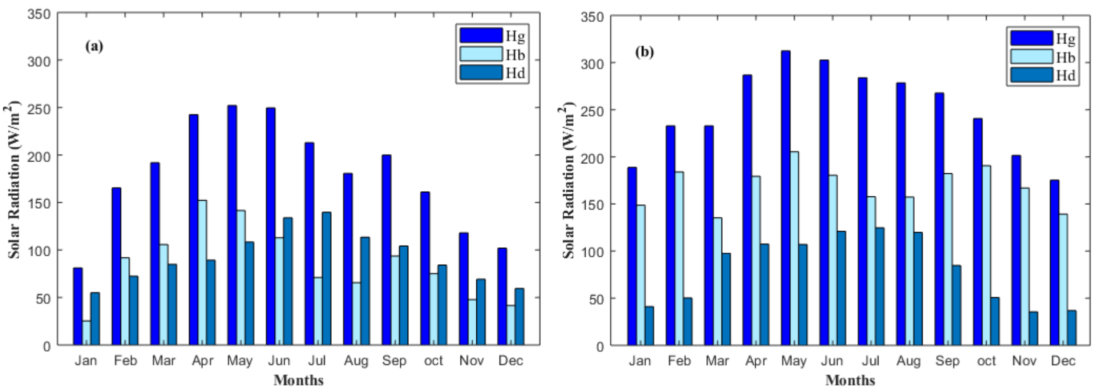

Fig. 2. Monthly Average Daily Global, Beam and Diffused Radiations for (a) Lahore and (b) Khuzdar

Fig. 2 gives the distribution of measured H_d with respect to the global horizontal irradiance throughout different the year. The intensity H_b is directly affected by the sunshine hours. In Lahore the peak values of beam radiations were found to be 152.2217 W/m^2 and 141.5594 W/m^2 for April and May respectively due to the plenty of available sunshine duration.

3. Methodology

The total solar radiations approaching the Earth were modeled as given by Eq. (2) and classified into three components; Beam or direct (H_B), Reflected (H_R) and the diffused (H_D) components of the radiations on a tilted surface. The radiations incident directly on the surface of solar PVs without any deviation are termed as beam radiations. The radiations received by the panel's surface after being reflected due to the phenomena of surface albedo are referred to as the reflected radiations while the radiations scattered into the atmosphere due to the clouds or suspended particles in the atmosphere are known as diffused radiations.

$$H_T = \left(H_g\text{-}H_d\right)\times R_b+H_d\, R_d +0.5H_g\times(1+\cos\beta) \qquad \text{(eq. 2)}$$

The reflected radiations on an inclined surface (H_R) were expressed in terms of global horizontal radiations (H_g) and surface albedo (ρ) in Eq. (2). Generally, a standard fixed value of 0.2 is widely used for the surface albedo. However, in the given case considering the fact that albedo for a natural surface keeps on varying, Eq.

(2) is fed with data set of hourly variation in the surface albedo acquired from MERRA-2. The daily average albedo which was estimated by utilizing the available data for hourly variation in the ground albedo was further used for the calculation of the average daily reflected radiations falling on the collector surface.

R_d represents the ratio of diffused radiations on inclined surface to the horizontal surface in Eq. (2). As the amount of diffused radiations depends upon a number of variable factors, R_d can be expressed as the function of different sky models corresponding to various sky conditions. Seventeen different sky models were selected from the literature to estimate R_d.

3.1 Isotropic sky models

Isotropic models are entirely focused on the isotropic part of the radiations as they are based on the assumption that scattering of radiations is constant over the sky dome. A detailed description of selected isotropic models is discussed in this section.

Liu and Jordan (Liu and Jordan, 1963)presented the simplest isotropic model for the estimation of empirical data for the cloudy skies. In circumsolar and horizon brightening were taken as zero. This model tends to perform well under the cloudy sky conditions as compared to the clear sky conditions. *Koronakis model* (Koronakis, 1986) with a few corrections to Liu and Jordan Model, was proposed in 1986. This improved version of Liu and Jordan Model enhanced the calculation accuracy for regions in Northern Hemisphere. *Badescu model* (Badescu, 2002) is also an advanced version of Liu and Jordan Model. This model defines the zenith angle and azimuth angle on the basis of 3D theory contrary to the Liu and Jordan Model that defines the zenith angle using the 2D theory. *Tian Model* (Tian et al., 2001) gives the approximation of diffused radiations striking the tilted surface while differentiating them from the global radiations. One of the positive aspects of Tian model is that it addresses the practical methods to link up total solar radiations incident on a surface to the atmospheric conditions.

3.2 Anisotropic sky models

The anisotropic models are based on the improved techniques which give the deep insights to analyze the diffused component of the solar radiations. The anisotropic models classified the distribution of the diffused solar radiations into two parts: the anisotropic scattering of diffused radiations around the Sun and the isotropic dispersion of the diffused radiations through rest of the sky dome.

Skartveit and Olseth Model (Skartveit and Olseth, 1986) estimate the beam and diffused components of the radiation on a tilted surface by utilizing the average monthly radiation data. It performs equally good with the constant albedo as well as the isotropic and seasonally varying albedo. For the case $H_b/H_o \geq 0.15$, corresponding to correction factor (Z) is 0, model tends to reduce to the Hay Model. *Hay Model* (Hay, 1979) only focused on the anisotropic distribution of diffused radiations and the anisotropic scattering in the rest of the sky region while ignoring the factor of horizon brightening. The circumsolar diffused radiations were estimated by using an anisotropic index F_{Hay}. Whereas, F_{Hay} is represented as the ratio of H_b to H_o. Hay model reduces to Liu and Jordan Model for the case F_{Hay} =0. *Reindl et al. Model* (Reindl et al., 1990) covered the anisotropic radiations around the Sun (circumsolar), isotropic radiations and the horizontal brightening. The circumsolar radiations: the scattering of diffused radiations around the Sun due to the suspended particles and the horizontal brightening and increased scattering of the diffused radiations near the horizon due to multiple reflections only occur in the clear sky. Due to this fact, both of these phenomena were not addressed in Liu and Jordan Model. *Steven and Unsworth Model* (Steven and Unsworth, 1980) calculates the diffuse coefficient by considering the radiations from both horizon brightening and sun's disk. *Willmot Model* (Willmott, 1982) introduces an anisotropic reduction factor for the inclined surface C_β. *Gueymard* (Gueymard, 1987) proposed to calculate the radiance of a partly cloudy sky as a weighted sum of the clear and overcast sky radiance as given by Eq. (3). N_g represents the Gueymard's weighting factor for cloud opacity. Since the cloudiness data is generally unavailable, Gueymard based the function N_g on solar radiation data: The clear sky radiation, R_{d0}, is given by a polynomial regression function of the solar altitude (or elevation angle), γ and β. The overcast sky radiation, R_{d1}, is defined as a function of β in radians.

Ma Iqbal Model (Iqbal, 2012) classifies the diffused radiations into two categories: the circumsolar diffused radiations and the radiations from rest of the sky zone. Atmospheric clearness index (K_T) was used to determine the extent of cloudiness. Eq. (4) gives the mathematical expression for the model. *Ma Iqbal Modified Model* (Iqbal, 2012; Steven and Unsworth, 1980) replaces the K_T with the modified clearness sky index K'_T. The modified clearness index allowed the computation without involving the solar zenith angle. *Muneer Model* (Muneer, 2007) estimated the intensity of diffuse radiation as given in Eq. (5). Whereas F_M is a composite clearness function depending on the particular sky and azimuthal conditions. For shaded surfaces and sun-facing surfaces under overcast sky conditions F_M is zero, while F_M is equal to F_{Hay} for clear sky and partly cloudy sky conditions. The tilt factor, T_M, represents the ratio of the slope background diffuse irradiance to the horizontal diffuse irradiance. Assuming clear sky conditions, *Temps-Coulson* (Temps and Coulson, 1977) modified the isotropic model by introducing two terms evaluating the diffuse radiation coming from the vicinity of the Sun's disc (P1) and the sky radiation from the region close to the horizon (P2) shown by Eq. (6). *Klucher Model* (Klucher, 1979) is the redefinition of Temps Coulson model by inserting a function f_k to determine the degree of cloud cover. The isotropic models which could only perform well under the overcast sky conditions, usually underestimate the irradiance under partly cloudy or clear sky conditions due to the concentrated intensity near the circumsolar region and horizon. The use of cloud cover degree was suitable to overcome such conditions. The Klucher model simplifies to the Liu-Jordan model when $f_k = 0$ *or* $H_d/H_g=1$ and reduces to Temps Coulson Model for $f_k = 1$ or $H_d/H_g=0$. *Perez Model* (Perez et al., 1990) as compared to other discussed models, uses the empirically derived coefficients to provide detailed insight for the analysis of circumsolar, isotropic and horizon brightening diffused radiations. The mathematical formulation of Perez model is given by Eq. (7). The brightness coefficients, F_1 and F_2 represent the radiations around the Sun and the region near the horizon respectively. Perez model reduces to Liu and Jordan model for the case $F_1= F_2= 0$. *Bugler Model* (Bugler, 1977) modified the isotropic model by adding terms for the diffuse radiation coming from the Sun's disc and for the radiation from the rest of the sky that depends on the angular height of the Sun over the horizon.

$$R_d = (1 - N_g)R_{d0} + N_g R_{d1} \quad \text{(eq. 3)}$$

$$R_d = K_T R_b + (1 - K_T)\left(\frac{1 + cos\beta}{2}\right) \quad \text{(eq. 4)}$$

$$R_d = T_M (1 - F_M) + F_M r_b \quad \text{(eq. 5)}$$

$$R_d = \left(\frac{1 + cos\beta}{2}\right) P_1 P_2 \quad \text{(eq. 6)}$$

$$R_d = (F_1 \frac{a}{b} + (1 - F_1)\frac{1}{cos\theta_{sza}}\left(\frac{1 + cos\beta}{2}\right) + F_2 \, sin\beta) \quad \text{(eq. 7)}$$

A MATLAB script was developed to find the total amount of radiations falling on the tilted surface using the discussed models. Measured solar radiations data for horizontal surface was used in a MATLAB script. In the script the input tilt angle is varied from 0-90° with interval of 1° for each day of year. The angle corresponding to which the daily H_T was maximum is termed as the daily optimum tilt angle. The monthly optimum tilt angle was found by varying the input tilt angle from 0° to 90° with an interval of 1° and corresponding total monthly average daily radiations were calculated at each angle. The angle at which total monthly average daily radiations are maximum gives the monthly optimum tilt angle of PV panel.

4. Results and Discussion

A comparison of all seventeen models was made from which a group including three isotropic models; Liu and Jordan Model, Koronakis Model and Badescu Model and three anisotropic models; Hay, MA Iqbal Modified and Gueymard models were selected based on their performance. The Gueymard model best estimated the diffused radiations for both of the selected sites. the mean annual irradiance on an inclined plane for Lahore with lowest sky K_T is 209.525 W/m^2 and 190.036 W/m^2 for daily optimum angle and annual optimum tilt angle respectively, and 326.054 W/m^2 and 288.88 W/m^2 for Khuzdar with highest K_T. Almost 16.67% increase in total annual mean irradiance on a tilted surface was observed compared to global horizontal irradiance (H_g) using the Gueymard diffuse model for Lahore. The same analysis for Khuzdar revealed that there is more than a 30 % increase in total annual mean irradiance on a tilted surface compared to H_g on a fixed horizontal surface. Among isotropic models, the Badescu showed the minimum value of total mean annual irradiance on the tilted surface and Koronakis model showed the maximum value of mean annual irradiance.

The total mean annual irradiance on tilted surface for Khuzdar was higher compared to Lahore. Hence, with increase in K_T, each given model best estimates the total irradiance on tilted surface. Anisotropic models show high estimation of total irradiance compared to isotropic models A comparison of the best performing anisotropic models shows that the variations in Hay model are closer to isotropic models. Also, the Gueymard model best estimates total irradiance on tilted surface among all isotropic and anisotropic diffuse models.

In winter due to the high θ_z, the inclination comes out to be greater than 10° to attain maximum solar irradiance, while in summer the daily optimum tilt angle was nearly zero. The daily optimum tilt angle ranges from 0-75° for Khuzdar and Lahore respectively. It was observed that anisotropic models were based on more accurate assumptions for sky conditions as maximum total irradiance was estimated for these models. Due to the greater K_T, Khuzdar witnessed a greater amount of incidence radiations. Further analysis showed that increase in total irradiance on the tilted surface relative to the H_g was strongly dependent upon the K_T. The correlation coefficients for the above-mentioned models were calculated. A high value of 0.913 with positive coefficient of correlation was obtained. This value was pertinent to the fact that a station with a greater value of mean annual K_T will result in an increase in total irradiance on the tilted surface relative to the H_g for a particular station. Also, the ratio of total radiations falling on the tilted surface is nearly 1.2 and 1.3 times of H_g for Lahore and Khuzdar respectively.

Gueymard model was observed to best estimate the total mean annual irradiance on tilted surface, while M.A Iqbal model dominated Gueymard model in winter month. The monthly mean daily total irradiance falling on the surface of PV panel corresponding to daily optimum tilt angle for isotropic and anisotropic models is shown in Fig. 3. A comparison among isotropic models and anisotropic models for monthly mean daily irradiance showed that anisotropic models estimate the high value of total solar irradiance on tilted surface. Among anisotropic models Gueymard model best estimate the total irradiance on a tilted surface with maximum solar radiations during the summer month. In winter solastic, Iqbal Modified model gives a promising estimation due to its modified K_T. Fig. 4 shows the monthly mean daily irradiance for latitude tilt. It was observed that the magnitude of monthly mean daily irradiance in any month corresponding to daily optimum tilt angle is higher than one estimated against latitude tilt.

Different values of H_T are found for various tilt angles in different months of the year. The angle at which the H_T reaches its maximum value refers to an optimal tilt angle. The optimum tilt angle for each month was different for each model. Monthly optimum tilt angles were computed using maximum monthly mean daily irradiance and was found that the monthly optimum angle for Khuzdar varies from 0° in June to 68° in July. The tilt angle was maximum in December month for every station. Depending upon the sky conditions and K_T the radiations incident on tilted surface were different, the maximum radiations were observed for Khuzdar with magnitude of 326.5028 W/m^2 in December. The minimum monthly optimum angle occurred in June for every station. The minimum radiations corresponding to the minimal optimum tilt angle occur for Lahore station having magnitude of 249.5495 W/m^2. It was also observed that the yearly average of daily optimum tilt angle or yearly optimum tilt angle is nearly equal to the latitude of the site. The yearly optimum tilt angle for Lahore and Khuzdar, is 27.14° and 28.58° respectively, and the latitudes of the sites are 31.6° and 27.8°.

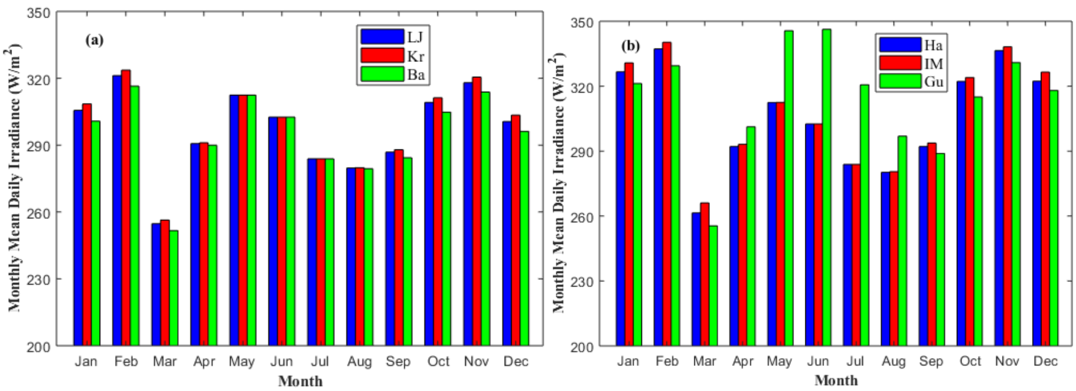

Fig. 3. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum Tilt Angles for Khuzdar

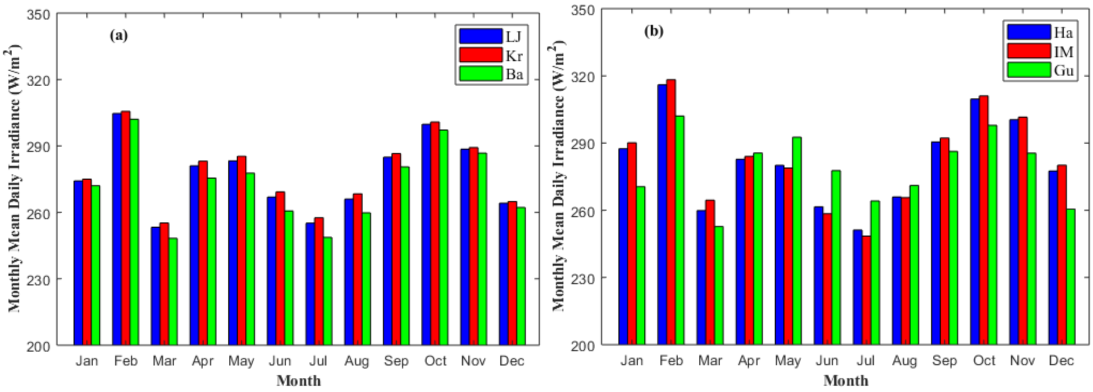

Fig. 4. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Khuzdar

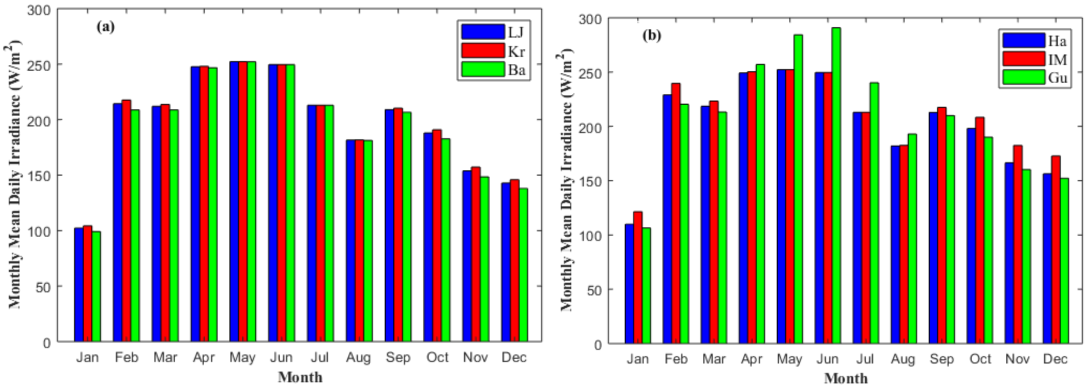

Fig. 5. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum Tilt Angles for Lahore

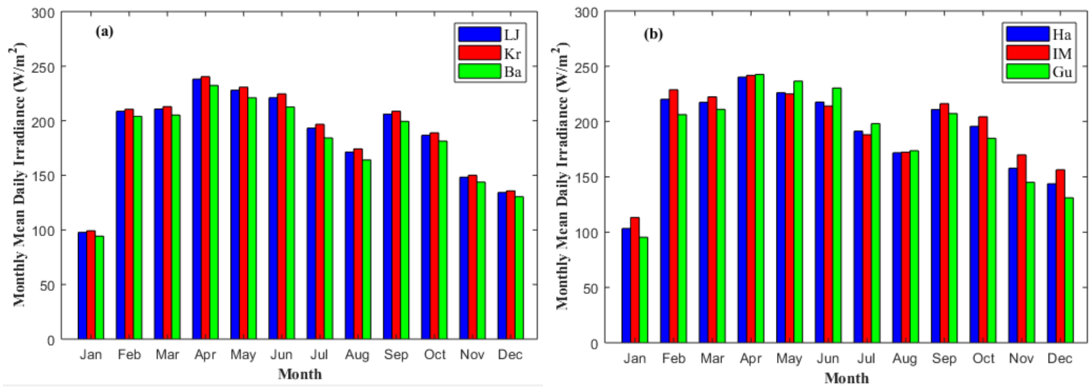

Fig. 6. Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Lahore

Fig.5 and Fig.6 present the comparison of monthly mean daily irradiance against the combination of selected six models for the monthly and latitude-based optimum tilt angle for Lahore. Gueymard model gives the maximum mean annual solar radiation of 209 W/m^2 incident on an inclined solar PV collector for daily optimum tilt angle. While MA Iqbal model performs best for the monthly solar radiations on the inclined surface.

A comparison of the percentage enhancement of H_T on a tilted surface between monthly optimum and latitude tilt for Lahore and Khuzdar is presented in Fig. 7. A minimum of 5% to 10 % enhancement in the collection of H_T is seen for Lahore while a 6% to 11% increase in the value of H_T is observed for Khuzdar. Using this information monthly optimum tilt angles for selected stations were computed against each solar diffuse model.

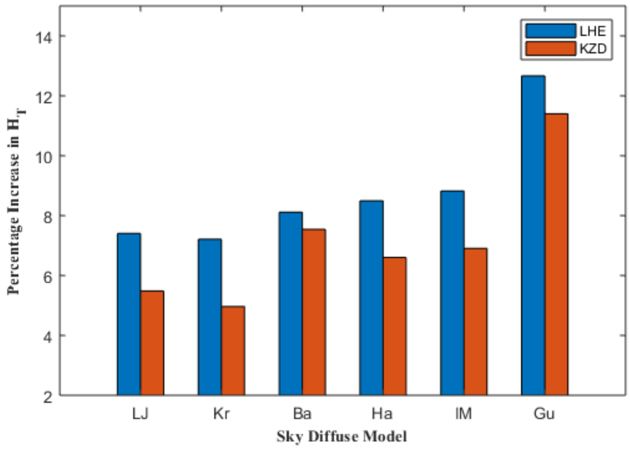

Fig. 7. Percentage Increase in H_T for Monthly Optimum Tilt as Compared to The Latitude Tilt

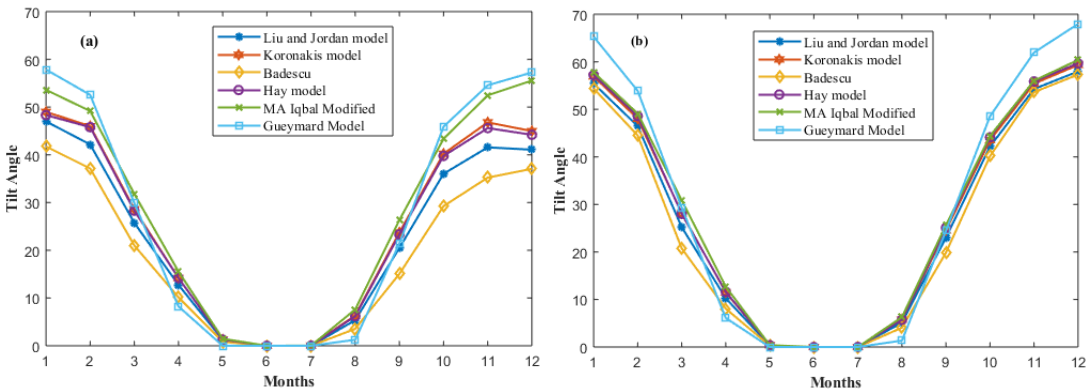

Fig. 8. Comparison of Monthly Optimum Tilt Angle for Isotropic and Anisotropic Sky Diffuse Models for (a) Lahore and (b) Khuzdar Stations

A comparison was also made between monthly optimum tilt angle for the selected stations against isotropic and anisotropic models. The results for Lahore which has the minimum K_T value of 0.49 and Khuzdar with maximum K_T of 0.68 are shown in Fig. 8.

The optimum tilt angle is dependent upon site latitude and declination angle. It can be seen that for any specific month the optimum tilt angle is different for every station and thus, varies with the site latitude. As the declination angle is increasing from December solastic to June solastic the optimum tilt angle is decreasing. From June to onwards the sun's declination angle starts increasing and corresponding to that the value of optimum tilt angle increases. During the month of the December the monthly averaged daily optimum tilt angle is 55.6° that falls to 0° in June/July during which the declination angle is from +23.17° to +21.37°

Monthly adjustment of solar PV to an optimum tilt as compared to annual tilt adjustment, allows the improved collection of H_T on the tilted surface. All the models are compared to observe the enhancement of total radiations impinging the tilted surface for selected sites.

5. Conclusion

A comparison was made between different isotropic and anisotropic sky models. The Gueymard model gives maximum mean annual solar radiation incident on an inclined solar PV collector for daily optimum tilt angle. The variations in optimum tilt angle for whole year were observed to be non-uniform. It nearly remains zero for Spring and Summer seasons, then it shows an increasing trend to 75° for Autumn and Winter seasons. The Gueymard model gives maximum mean annual solar radiation incident on an inclined solar PV collector for daily optimum tilt angle. While M.A Iqbal model performs best for the monthly solar radiations on inclined surface due to modified value of K_T. Almost for all locations the sun follows longer path in summer season, and daily optimum tilt angle in these months is nearly 0°, while in winter solastic the daily optimum tilt angles are maximum as the sun tracks a shorter path. This maximum daily optimum tilt angle is found to be nearly 75° for Lahore and it occurs in December. The yearly fixed optimum tilt angle for solar PV panels in Lahore and Khuzdar is nearly equal to the latitude of the site. More than 11% and 13% increase in monthly mean daily irradiance on the tilted surface is observed compared to irradiance on a horizontal surface for Lahore and Khuzdar stations respectively. The ratio of total mean annual radiations falling on the tilted surface is nearly 1.2 and 1.3 times of H_g for Lahore and Khuzdar respectively. The amount of solar irradiance on a tilted surface shows a good agreement with the K_T. A site with a greater sky clearness index will experience a higher amount of solar irradiance. Almost a 6-11% increase in the H_T is observed for monthly optimum tilt as compared to the latitude for both Lahore and Khuzdar.

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