Dual Axis Optimization of Solar Photovoltaic at Various Sites in Pakistan

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Abstract

This study aims to estimate solar irradiance of dual axis solar photovoltaic (PV) based on measured solar radiation data for nine stations in different climatic conditions. Six different sky models (isotropic and anisotropic) were compared to estimate the diffused component of the solar radiation incident on the PV surface. The optimum tilt and azimuthal angles were evaluated for one year using measured data. Solar radiation components (beam, diffused and reflected) were estimated by varying the tilt angle from 0° to 90°. The solar radiation on a tilted surface depends on the clearness index (K_T) with a correlation coefficient of 0.913. The total radiation on tilted surfaces is 1.2 and 1.3 times global horizontal irradiance (H_g) for Lahore and Khuzdar respectively. The annual mean irradiance on tilted surface for daily (annual) optimum tilt angle is 326.1 W/m^2 (190.0 W/m^2) and 209.5 W/m^2 (288.9 W/m^2) for respective sites. The mean monthly total radiation for these models shows an almost 6 to 11 % increase with monthly optimum tilt angle compared to latitude tilt angle for both sites. The maximum (minimum) azimuth angle is noted for June (December), which varies from -113.8° to 113.8° (-58.3° to 56.9°). The maximum mean monthly total irradiance for the optimum dual axis system is 630.9 W/m^2 (Lahore), 709.0 W/m^2 (Karachi) in April while 907.2 W/m^2 (Khuzdar) in February, and 884.0 W/m^2 (Quetta) in November. The comparison between the mean monthly total irradiance obtained using optimum tilt angle and dual axis tracking of PV collector shows an increase of about 7 to 26 % for both sites.

Keywords: Dual Axis Tracking, Optimal Azimuth Angle, Optimal Tilt Angle, Isotropic models, Anisotropic models

1. Introduction

The increasing energy demand and fossil fuel depletion have led to an increased demand for the rapid development of alternative energy resources. Fossil fuels are the primary source of energy generation and it generates energy up to 85 % for domestic and commercial use all around the globe (Bauen, 2006). Fossil fuel emissions (SO_x, NO_x, carbon monoxide and Hydrocarbons) are the major cause of ozone depletion and subsequent increases in global warming and air pollution. Different alternative energy resources are being utilized for power generation. Renewable energy resources (solar, wind, hydroelectric, geothermal, etc.) are the fastest growing energy alternatives due to their environment-friendly nature (Converse, 2006; Ellabban et al., 2014; Panwar et al., 2011). Solar energy is one of the best alternative resource for energy generation due to its huge potential and easy deployment on both smaller and larger scales (Li et al., 2015; Sefa et al., 2009).

Solar energy is being utilized to generate power using solar conversion devices such as photovoltaics (PVs) and Concentrated Solar Power (CSP). The output power generated by the solar conversion device is quantified by the radiation collected (Yao et al., 2014). The lower efficiency of these devices urges the implementation of some optimal way to enhance the power output by increasing the amount of incident radiations on the PV surface. The solar radiation incident over the surface can be improved by tracking the solar PV with sun orientation, which will eventually enhance the performance of the solar collectors. The output power of solar PVs can be enhanced by optimizing the azimuthal and tilt angle based on orientation of sun (Chang, 2010; Kaddoura et al., 2016).

The tilt angle optimization involves the conversion of global and diffuse horizontal solar radiation data into the tilted surface data (Demain et al., 2013). The total solar radiation (H_T) composed of beam radiations (H_B) (incident directly over the surface without any hindrance due to aerosol or cloud), reflected (H_R) radiations (incident after reflected from different surfaces) and diffused (H_D) radiations (scattered radiations due to aerosol or clouds radiations) (Drummond, 1956; Suckling and Hay, 1977). The tilted beam irradiance was estimated using the ratio of beam radiation for tilted to the horizontal PV surface (Huld et al., 2012). It is difficult to evaluate the diffused component of radiation as it depends upon various factors such as humidity, sky condition, clearness index (K_T), and turbidity. The researchers have suggested different techniques to estimate diffuse components of the radiations using maximum influencing factor (Duffie et al., 1994).

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Isotropic models are the simplified methodology for estimating diffused radiation by assuming the uniform scattering of radiation over the sky dome, while anisotropic models are the detailed insights considering both isotropic and anisotropic parts of the diffused radiations. Different isotropic and anisotropic models have been presented for estimating the diffused radiation component on a tilted surface. The formulation is based on the clearance index (K_T), solar hour, and relative humidity (R_h). Reindl et al. (Reindl et al., 1990) proposed their model based on the isotropic and anisotropic parts of diffused radiation and selected four significant factors from a set of 28 significant factors. Noorian et al. (Noorian et al., 2008) proposed the comparison of the performance of twelve different isotropic and anisotropic models at Karaj (35°55′N; 50°56′E) Iran to evaluate diffused radiation on the tilted surface for south and west-facing irradiance. The beam and ground reflected radiation estimation remain the same for all the isotropic and anisotropic models, whereas the diffused component is estimated using different techniques.

The azimuthal angle (γ) can be optimized by regulating different factors such as declination angle (δ), solar zenith angle (θ_z), solar inclination angle (α_s), and incident angle (θ_i) based on earth orientation. The surface is tracked with the sun radiation throughout the day from sunrise at a solar zenith angle (θ_z) of -85° to sunset, where it is 85° based on radiation, that is collected for 10 minutes from Jan 01 to Dec 31, 2016.

Sidek et al. (Sidek et al., 2017) proposed a self-positioning solar tracker with a precision control system for elevation and azimuthal angle. The result reveals a 12.8% and 26.9% increase in power than fixed-tilted collectors for heavy and clear overcast conditions. Abdallah, S. and Nijmeh, S. (Abdallah et al., 2004) conducted an experimental study based on the electromechanical dual-axis solar tracking system, controlled by a programmable logic controller (PLC) and investigated the effect of dual-axis on the output performance. The study reveals the increase of 41.34% collected energy as compared to a fixed PV system tilted at 32°. An experimental study was conducted to investigate the electrical power generation and the current-voltage characteristics for different types of a solar tracking system such as dual-axis, one axis east-west, one axis north-south and one axis vertical using flat-plate photovoltaic. The result illustrates the increase in volt-current characteristic and it was found that the recorded power gain for two axes was 43.87% with 37.53% for east-west, 34.43% for vertical and 15.69% for north-south tracking than a fixed PV system, the motor and control system energy consumption was less than 2% of the total collected energy (Abdullah and Management, 2004).

2. Methodology

The total solar radiation incident over the earth surface was classified into three components i.e., Direct or Beam radiation (H_B), diffused Radiation (H_D), and ground Reflected (H_R), as expressed by Eq. (1). Beam radiation incident directly over the solar PV surface without any deviation. The ground reflected are the beam incident over the surface after reflecting from the atmosphere due to phenomena of surface albedo as given by Eq. (2), while the diffused radiations are the scattered radiation incident over the PV surface because of the suspended particle and cloud in the atmosphere.

$$H_T = H_B + H_D + H_R \quad (1)$$

$$H_T = \left(H_g - H_d\right) \times R_b + H_D + 0.2 H_g \times (1 + \cos\beta) \quad (2)$$

R_b represents the ratio of average daily beam radiations on tilted to the horizontal surface can be defined in terms of sunrise hour angle on horizontal (ω_s) and tilted (ω'_s) surface, latitude (ϕ) of the location in the northern hemisphere sloped towards equator, tilt angle (β) and declination angle (δ). The reflected radiation on an inclined surface (H_R) was expressed in terms of global horizontal radiation (H_g) and surface albedo (ρ). Generally, a standard fixed value used for surface albedo is 0.2, however, the surface albedo varies with time, and the hourly data is utilized for the surface albedo acquired from MERRA-2. The estimation for the daily average albedo calculated by the available ground albedo data was further used to calculate the average daily reflected radiation incident over the solar surface. R_d is a variable factor that can be estimated by sky models. Six sky models are selected to estimate the R_d. H_D is calculated from H_d and R_d using Eq. (3).

$$H_D = H_d R_d \quad (3)$$

Isotropic sky models are based on the assumption that the scattering of solar radiation is constant over the sky dome. The selected isotropic models include Liu and Jordan Model (LJ) (Liu and Jordan, 1961), Badescu Model (Ba) (Badescu, 2002), and Koronakis Model (Kr) (Koronakis, 1986).

The Liu and Jordan model is the base of multiple isotropic sky models, which best estimate the diffused radiation in cloudy sky. His proposed equation to estimate R_d mentioned as Eq. (4) relates the cloudiness index, extra-terrestrial and total solar radiation striking on the surface. Koronakis is an advanced form of Liu and Jordan model. It was proposed in 1986 to estimate the diffused radiation in Northern Hemisphere more accurately as given by Eq. (5). Liu and Jordan model defines the zenith angle on the basis of 2D theory, while Badescu model contradicts and defines the zenith and azimuthal angle based on the 3D model as shown by Eq. (6).

$$R_d = \frac{1}{2}(1 + \cos\beta) \tag{4}$$

$$R_d = \frac{1}{3}(2 + \cos\beta) \tag{5}$$

$$R_d = \frac{1}{4}(3 + \cos(2\beta)) \tag{6}$$

Anisotropic models are the advanced method to investigate diffused radiation. They estimate the anisotropic and isotropic diffused radiation around the sun and the rest of the sky. The anisotropic models include Hay Model (Ha) (Hay, 1979), Perez Model (Pr) (Perez et al., 1990), Ma Iqbal Modified Model (IM), and Gueymard Model (Gu) (Gueymard, 1987).

Hay model neglected the horizontal brightening factor and assumes isotropic and circumsolar are the only two components of diffused radiation. The proposed relation to estimating the R_d is given in Eq. (7). While MA Iqbal proposed a model assuming that diffused radiation consists of radiation emitted by the circumsolar region and the rest of the sky. MA Iqbal modified model is modified form of MA Iqbal model which is proposed by the Perez. He suggested to replace the clearance index factor K_t to modified clearance index factor K_t', which is given in Eq. (8). Gueymard 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. (9)

$$R_d = \left(\frac{H_b}{H_o}\right) R_b + \left(1 - \frac{H_b}{H_o}\right)\left(\frac{1 + \cos\beta}{2}\right) \tag{7}$$

$$K'_T = \frac{K_T}{1.031 \exp\left(\frac{-1.4}{0.9 + \frac{9.4}{M}}\right) + 0.1} \tag{8}$$

$$R_d = (1 - N_g)R_{d0} + N_g R_{d1} \tag{9}$$

The above-listed models are utilized to estimate the diffused radiation. The monthly mean and daily mean solar irradiance for Lahore and Khuzdar is estimated on optimum and latitude fixed tilt angles.

3. Result and Discussion

The maximum solar insolation was calculated using six best performing models that includes three isotropic models (Liu-Jordan Model (LJ), Koronakis Model (Kr), Badescu Model (Ba), and three anisotropic models (Hay Model (Ha), MA Iqbal Modified (IM) and Gueymard Model (Gu)) respectively. The Gueymard model gives the best estimation of diffused radiation. The mean annual irradiance on an inclined plane for daily optimum angle and annual optimum tilt angle for Lahore with the lowest sky K_T is 209.525 W/m^2 and 190.036 W/m^2 respectively, and for Khuzdar it is 326.054 W/m^2 and 288.88 W/m^2 with highest K_T. The total annual mean irradiance on a tilted surface increases up to 16.67% compared to global horizontal irradiance (H_g) using the Gueymard diffuse model for Lahore. The same analysis revealed 30% enhancement in total annual mean irradiance on a tilted surface as compared to H_g on a fixed horizontal surface for Khuzdar.

The incident radiations at Khuzdar are high due to greater K_T. 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 coefficient was calculated and comes out to be 0.913, which shows that the greater value of mean annual sky clearness index will increase total irradiance on the tilted surface compared to H_g for that specific station. Also, the Gueymard model best estimates total irradiance on the tilted surface among all isotropic and anisotropic diffuse models. 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. 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 estimates the total irradiance on a tilted surface with maximum solar radiations during the summer month. Fig. 5 shows that the monthly mean daily irradiance in any month corresponding to daily optimum tilt angle is higher than one estimated against latitude tilt.

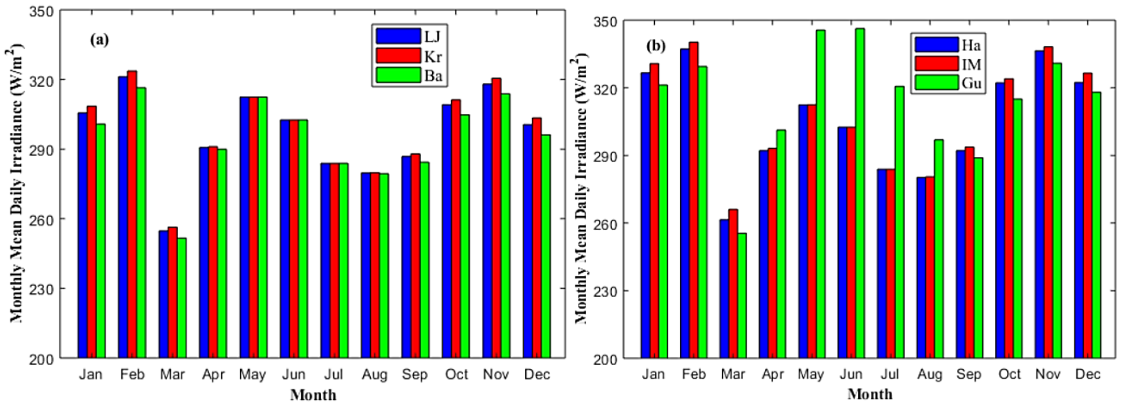

Fig. 1: Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum

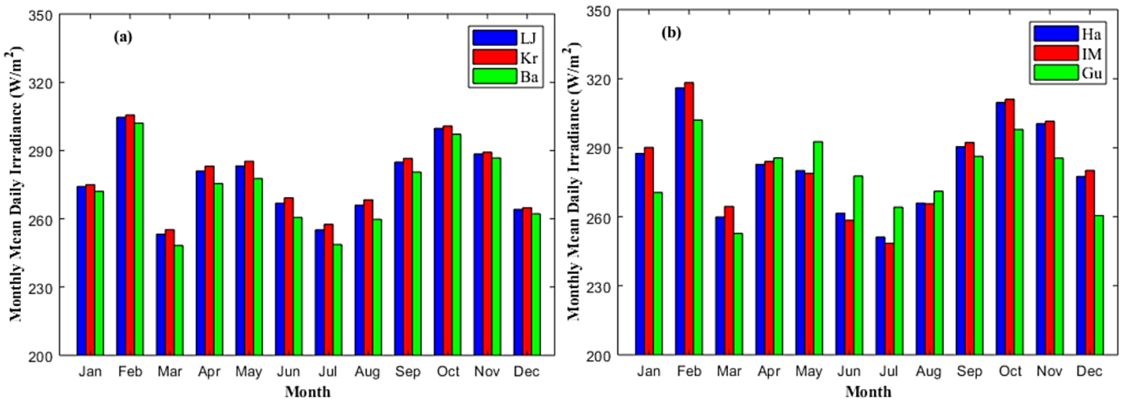

Fig. 2: Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Khuzdar

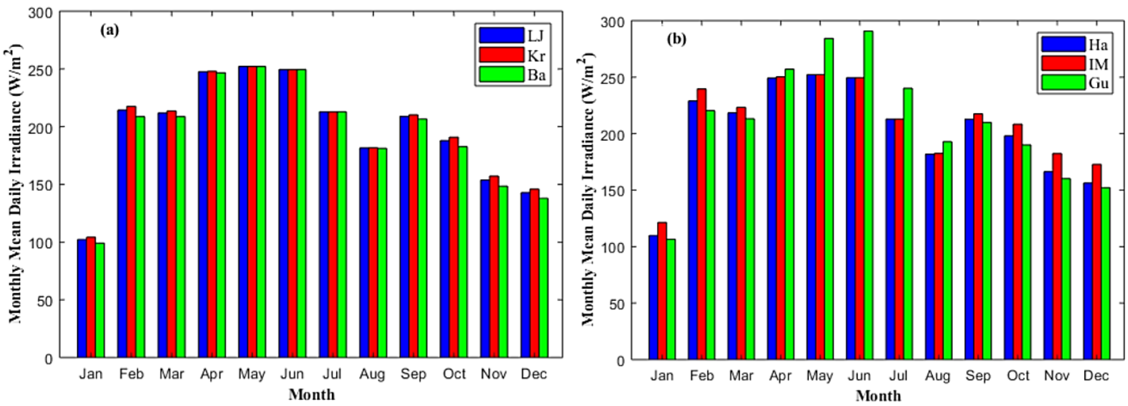

Fig. 3: Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Daily Optimum Tilt Angles for Lahore

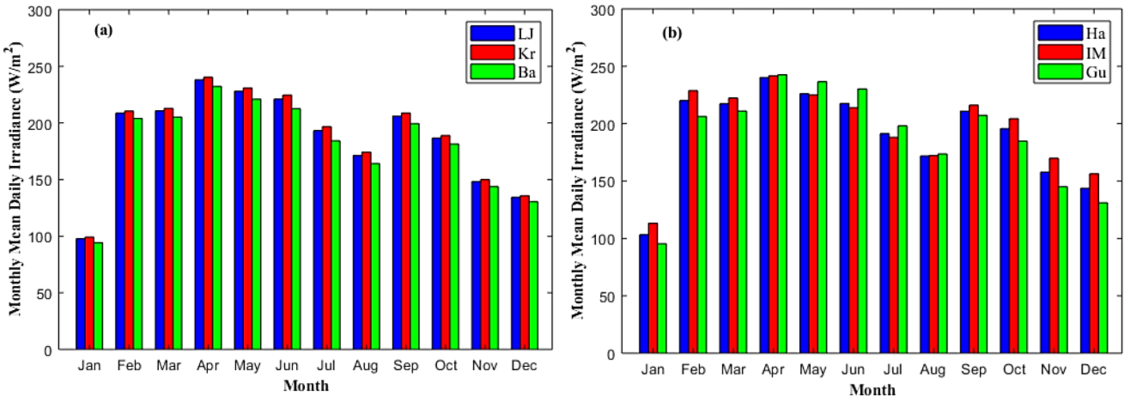

Fig. 4: Comparison of Monthly Mean Daily Irradiance (a) Isotropic and (b) Anisotropic Sky Diffuse Models for Latitude Fixed Tilt Angles for Lahore

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 for Khuzdar by using maximum monthly mean daily irradiance, varying from 0° in June to 68° in July. The maximum tilt angle value for every station was observed in December, and its minimum was in June. The radiations on the tilted surface differed based on the sky condition and sky clearance index. The maximum radiations for Khuzdar were observed to be 326.5028 W/m^2 in December. The yearly average of the daily optimum tilt angle is observed to be the site latitude. The minimum radiation for Lahore station comes out to be 249.5495 W/m^2 for the corresponding minimum optimum tilt angle. The yearly optimum tilt angle is 27.14° and 28.58° for Lahore and Khuzdar respectively, having latitudes of 31.6° and 27.8°.

A comparison of monthly mean daily irradiance for the combination of six selected models for the monthly and latitude-based optimum tilt angle for Lahore is illustrated in Fig. 3 and Fig. 4 and it shows that for daily optimum tilt angle, the Gueymard model gives the maximum mean annual solar radiation of 209 W/m^2 incident on an inclined solar PV collector. Fig. 5 depicts the percentage enhancement of total irradiance incident on a tilted surface between monthly optimum and latitude tilt for Lahore and Khuzdar. The result shows the minimum enhancement in total Irradiance for Lahore is 5 % to 10 %, while for Khuzdar, it is 6 % to 11%. This information is used to compute the optimum tilt angle for selected stations against each diffused sky model.

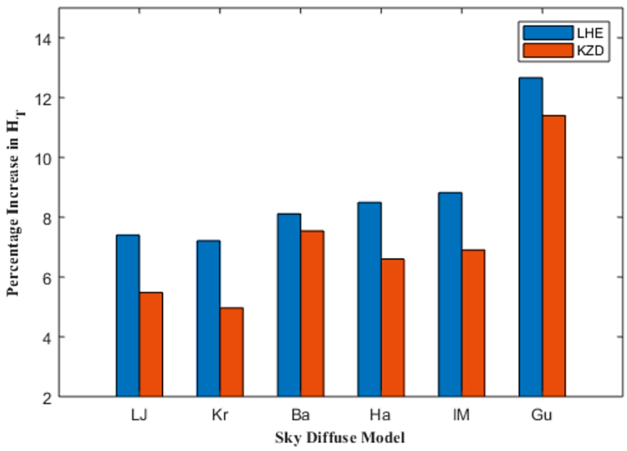

Fig. 5: Percentage Increase in H_T for Monthly Optimum Tilt as Compared to The Latitude Tilt

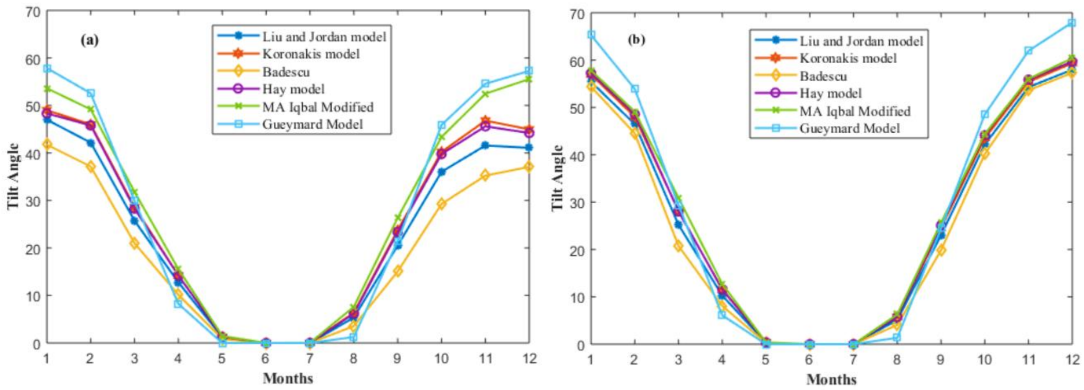

Fig. 6: Comparison of Monthly Optimum Tilt Angle for Isotropic and Anisotropic Sky Diffuse Models for (a) Lahore and (b) Khuzdar

The monthly optimum tilt angle against the isotropic and anisotropic models for the selected station were compared. Fig. 6 depicts the results for Lahore having a minimum K_T value of 0.49 and Khuzdar with a maximum K_T value of 0.68. The analysis shows that the optimum tilt angle for any specific month is different for every station as it depends on the latitude and declination angle of that site. The optimum tilt angle decreases from December solastic to June solastic as the declination angle increases and the radiation angle becomes steeper. From June onwards, the increase in declination angle causes an increase in the tilt angle as the radiation incident with a shallow angle on the earth's surface. The monthly averaged daily optimum tilt angle is 55.6° in December that decreases to 0° in June/July during which the declination angle varies from +23.17° to +21.37°. The total irradiance incident on the tilted surface is enhanced by the monthly adjustment of solar PV to an optimum tilt compared to annual tilt adjustment.

These models are compared in terms of maximum total solar irradiance (H_T) for the eight sites, as shown in Fig. 7 (a). The Gu-model best estimates the diffused radiations. The annual mean irradiance on tilted surface for daily (annual) optimum tilt angle is 326.05 W/m^2 (190.03 W/m^2) and 209.52 W/m^2 (288.88 W/m^2) for Lahore and Khuzdar respectively. The total irradiance on a tilted surface increases up to 16.67 % (Lahore), and 30 % (Khuzdar) compared to global horizontal irradiance (H_g) on a fixed horizontal surface using the Gueymard (Gu) diffuse model.

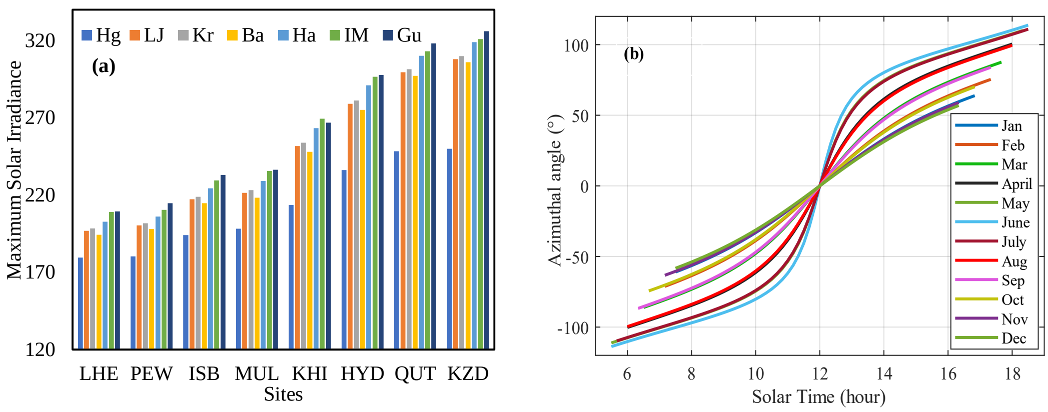

Fig. 7: Variations of (a) maximum solar irradiance for all sites and (b) Azimuthal angle for Lahore for 21st day of each month for a year (2016)

The solar irradiance on a tilted surface depends on the clearness index (K_T) with a correlation coefficient of 0.913, this shows that maximum H_T can be obtained using a flat plate collector at an optimum tilt angle. The solar PV collector tracking is from east to west facing south direction and azimuthal angle is zero at solar noon. The azimuthal angle varies from -113.81° to 113.81° throughout the day with a maximum range of variation in June as shown in Fig. 7 (b). The range of the solar PV tracking system decreases in winter season, with lowest range of -58.32° to 56.89° in December.

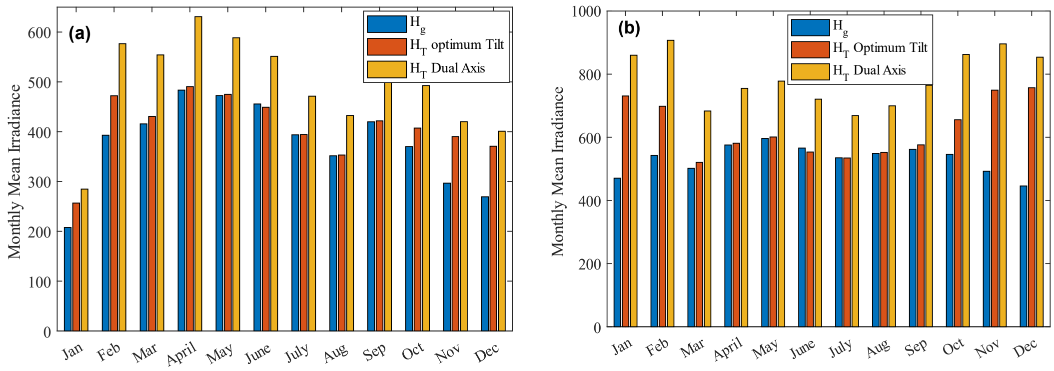

Fig. 8: Comparison of mean monthly total irradiance for optimum tilt and dual axis with Global Horizontal Irradiance (H_g) for a) Lahore b) Khuzdar

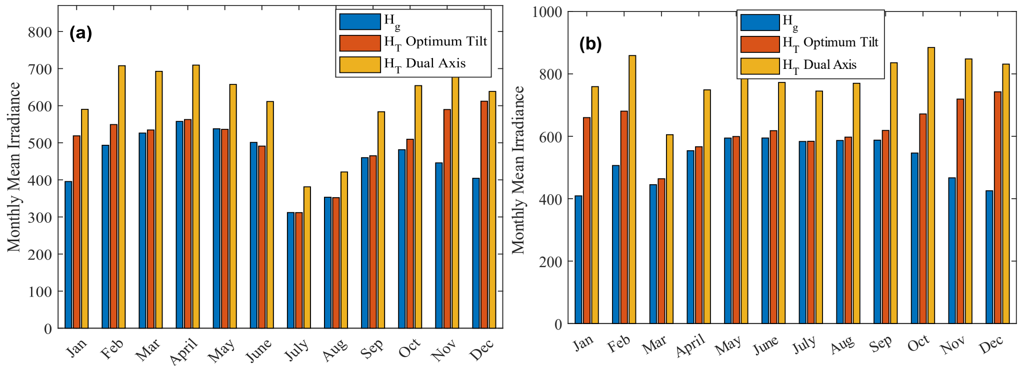

Fig. 9: Comparison of mean monthly total irradiance for optimum tilt and dual axis with Global Horizontal Irradiance (H_g) for a) Karachi b) Quetta

The maximum mean monthly total irradiance for the optimum dual axis system is 630.89 W/m^2 (Lahore) in April and 907.19 W/m^2 (Khuzdar) in February as shown in Fig. 8. The maximum mean monthly H_T for the tilted surface is increased up to 22.30 % and 24.67 % using dual axis tracking of collector for Lahore and Khuzdar respectively. Fig. 9 shows the result for monthly mean irradiance for Karachi and Quetta, the maximum irradiance for Karachi is 709W/m^2 and for Quetta is 884W/m^2 in April and November respectively, and shows the enhancement up to 22.82% and 25.96% for respective Sites while comparing with the single axis (Tilt) tracking.

4. Conclusion

This study was conducted to estimate the total irradiance on a fixed flat, single axis tracked and dual axis tracked surfaces. The irradiance on the fixed flat surface is total horizontal irradiance H_g. The mean radiation falling on a PV surface for annual and daily optimum tilt angle was calculated using six different isotropic and anisotropic sky models. The comparison shows that the Gueymard model gives the maximum mean yearly solar radiation incident on an inclined PV collector. Four different cities of Pakistan (Lahore, Khuzdar, Karachi and Quetta) were discussed in this study. A non-uniform variation in optimum tilt angle is observed; it remains nearly zero in spring and summer while increasing to 75° for autumn and winter. The total irradiance on a tilted surface increases more than 16 % and 30 % compared to Hg.

The optimum dual axis tracking was performed by adjusting the PV collector position with the orientation of sun from sunrises to sunset. The maximum solar were irradiance of Khuzdar is 907.19 W/m^2 which is maximum compared to the other sities, because of its high clearance index value of 0.69. An increase of 7 to 26 % was observed in mean monthly total irradiance using the optimum dual axis tracking compared with optimum tilt angle of PV collector.

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