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Araştırma Makalesi / Research Article

Calculate the Optimum Slope and Surface Orientation Angles of PV Panels in the City of Istanbul, Türkiye

Türkiye'nin İstanbul Şehrindeki PV Panellerinin Optimum Eğim ve Yüzey Oryantasyon Açılarının Hesaplanması

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ABSTRACT

Because of the shadow of high buildings and huge urban development that the world is witnessing, especially in the large cities such as Istanbul, this led to prevent taking advantage from a large part of the falling solar radiation, which led to finding alternative solutions for the purpose of benefiting from the falling solar radiation. Among these solutions is the adjusting solar panel at the optimum slope and orientation angle. So the purpose of this study is to determine the optimum slope and orientation angle for a photovoltaic panel in Istanbul (Turkey) with coordinate of (41° 1′ 0″ N, 28° 58′ 0″ E), latitude of (Ø = 41.0167), and explain the effect of azimuth angle on the optimum slope angle of solar radiation on the photovoltaic panel. A mathematical model was developed by Klein and Theilacker to determine any surface azimuth angle (Υ) was used to estimate the total solar radiation on the slope photovoltaic panel surface, also Liu – Jordan model was used for calculating the optimum tilt angle for south face direction and then comparison results with two models. In our study we used a Microsoft Excel spreadsheet to determine optimum slope (β) and azimuth (orientation) (Υ) surface angles for any city only by changing the coordinate and horizontal solar radiation of the selected city. For calculation purposes, horizontal solar radiation data for the city of Istanbul was obtained from the prediction of worldwide energy resources (power) by NASA. The optimum tilt (β) and azimuth (Υ) angles were determined by searching for the values of angles for which the total radiation on the PV surface was maximum throughout the year. And for the specific azimuth angle (Υ) changes from (0 to 90) degree It is found that the optimum tilt angle (β) should be changed to observe the maximum solar radiation. The annual maximum solar radiation in Istanbul city for azimuth angle greater than 0^o was 6033 Mj/m^2 at azimuth angle equal to 10^o and tilt angle equal to 30^o.

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ÖZ

Dünyada özellikle İstanbul gibi büyük kentlerde bulunan yüksek binaların ve bu binaların meydana getirdiği gölgelerin özellikle büyük başkentlerde güneş ışınımının büyük bir kısmından yararlanılmasını engellemiş olması nedeniyle düşen güneş ışınımından yararlanma için alternatif çözümler aranmasına yol açmıştır. Güneş panelinin optimum eğim ve yönlendirme açısında ayarlanması bu çözümler arasında yer almaktadır. Bu nedenle bu çalışmanın amacı, İstanbul'da (Türkiye) 41° 1' 0'' K, 28° 58' 0'' D koordinatlarınada, Ø = 41.0167 enlemdeki fotovoltaik panel için optimum eğim yönlendirme açısı belirlemek ve fotovoltaik panelde güneş ışınımının optimum eğim açısına azimut açısının etkisini açıklamaktır. Eğimli fotovoltaik panel yüzeyindeki toplam güneş ışınımını tahmin etmek üzere herhangi bir yüzey azimut açısını (ϒ) belirlemek için Klein ve Theilacker tarafından geliştirilen bir matematiksel model kullanılmıştır. Ayrıca güney yüz yönü için optimum eğim açısını hesaplamak üzere Liu – Jordan modeli kullanıldıktan sonra iki modelden elde edilen sonuçlar karşılaştırılmıştır. Çalışmamızda, herhangi bir şehir için optimum eğim (β) ve azimut (oryantasyon) (ϒ) yüzey açılarını belirlemek üzere seçilen şehrin koordinatı sabit tutularak farklı yatay güneş ışınımları için bir Microsoft Excel elektronik tablosu oluşturulmuştur. İstanbul yatay güneş radyasyonu verileri, NASA tarafından dünya çapındaki enerji kaynaklarının (power) tahmininden elde edilerek hesaplamalar için kullanılmıştır. Optimum eğim (β) ve azimut (ϒ) açıları, yıl boyunca PV yüzeyindeki toplam radyasyonun maksimum olduğu açıların değerleri aranarak belirlenmiştir. Spesifik azimut açısı (ϒ) için (0 ila 90) derece arasında değiştiği maksimum güneş radyasyonunu gözlemlemek için optimum eğim açısının (β) değiştirilmesi gerektiği bulunmuştur. İstanbul şehrinde 0'dan büyük azimut açısı için yıllık maksimum güneş radyasyonu, 10 azimut açısına ve 30 eğim açısına eşit olduğunda 6033 Mj/m^2 olduğu belirlenmiştir.

1. INTRODUCTION

Solar energy is one of the clean and renewable energies that humans can use and benefit from it. It is one of the best energies that currently used in abundance due to the continuous decrease of traditional energies and their negative effect on the environment [1]. The sun is the main source of the Earth's heat, and the rays emanating from it are called solar radiation. The optimum tilt or slope (β) and surface azimuth or orientation (Υ) angles are the important factor that used in the calculations and determined the optimum solar radiations and they depend on the position of the sun, latitude and local geographical characteristics [2]. Most of researcher studied the effect of tilt angle on the solar radiations for pv panels that install in south facing, because of good results, but sometimes there are some difficulties to install it in the south face, so we have to calculate the appropriate orientation angle (Υ) to get the best solar radiation. Turkey occupies a privileged position that allows it to benefit from the falling solar radiation that is about 2,640 hours per year also the high average daily solar density that equal to 3.6 kWh/m^2 [3]. Klein *et al.* [4], developed an algorithm model to calculate any surface azimuth angle in the southern and northern hemisphere to estimate the ratio of monthly average total radiation on an inclined surface to that on a horizontal surface [4]. Shahnawaz *et al.* [5], determined the optimum slope angle by using nine new models in the region of Sindh, Pakistan. They determined the optimum slope angles for monthly, seasonally, half-yearly and yearly. Finely they found from results that slope of tilt angle various from 0^o in May, June and July to 49^o in December [5]. Yuexia *et al.* [6], developed mathematical model to calculate the optimum tilt angle and orientation of the Pv panel installed in Lhasa through summer season. They conclude that there is a deviation about 5 degree in the optimum orientations [6]. Mamun *et al.* [7], investigated numerical method that used to select the optimum slope angle for the photovoltaic panel installed in Bangladesh. The results showed that the optimum slope angle of some cities like Dhaka, Jessore, and Ishurdi was 25^o, 30^o, 25^o respectively [7]. Hailu *et al.* [8], used the isotropic and anisotropic models to determine the optimum tilt and orientation angles for the city of Toronto in Canada, they conclude from study that by using four isotropic models there was a varying in optimum tilt angles from 37^o to 44^o and for other models (anisotropic) there was varying range between 46^o to 47^o [8]. Abdullahi *et al.* [9], developed two computer programs to calculate the optimum slope angle and its effect on the solar radiation monthly and seasonally for the city of Kano, Nigeria [9]. Maref *et al.* [10], hailuused SPSS software and statistical verifications method to compare the accuracy of real data with simulation data in Montreal in different seasons. The results showed that the optimum tilt angles in summer season arrange from 27.5^o to 35^o [10]. Khan *et al.* [11], studied the effect of different tilt angles on the performance on the photovoltaic panel for some articles deals with this subject area [11]. Nfaoui *et al.* [12], used a program by MATLAP software to obtain the solar radiation for any inclined angle. They installed the PV for the purpose of collecting data in the faculty of science and technology of Settat in Morocco [12]. Abdallah *et al.* [13], compared the results obtained by MATLAP software for calculate the optimum tilt angle in Palestine on a south facing with the photovoltaic software developed by US national renewable energy laboratory. They conclude that there is a good similar between the results [13]. Oh *et al.* [14], analyzed the calculation model for derived the tolerance angle. Also they derived a simple formula for theoretical calculations. Finally they conclude that for a tolerance angel of 1%, 5% and 10% the loss of irradiance were 9^o, 21^o and 30^o respectively [14]. Luting *et al.* [15], investigated an optimum tilt and azimuth angle in the high mountains and complex terrain by using a clear sky model. The study region was in Batang county and Dege county in Western Sichuan Plateau of China. Finally the results showed that the energy collection was 238.72 kWh/m2 and 398.33 kWh/m^2 per year [15]. Somil *et al.* [16], studied the development of BIPV system to estimate the optimum azimuth and tilt angle for the high and shadow buildings [16]. Qusay *et al.* [17], determined the optimum tilt angle for eighteen provinces in Iraq. The results showed that the optimum tilt angle was in range from 0^o to 64^o [17]. Ashutosh *et al.* [18], computed the optimum tilt angles for different months for the city of Hamirpur, Himachal Pradesh in India by developing a three mathematical model. They suggested that by using the model of third degree polynomial provide a good accuracy [18]. Tong *et al.* [19], calculated the Keplerian orbit parameters of the sun to investigate a model for calculating the optimum angle of solar collector. The results showed that the optimum tilts angle various from 30° on 1 January to 76.1° on July [19]. Rauf *et al.* [20], presented a new model for calculation the best panel direction in the mountain region for the day [20]. Yadav *et al.* [21] determined by a numerical method optimum slope and orientation angle of building integrated photovoltaic (BIPV) system. They found from results that for D/H ratios 7.5/15, 9/15, 12/15, 15/15, 18/15, and 24/15 are 12, 7.5, 3.5, 1.5,1 and 0, respectively [21]. As shown from previous studies there is a few papers in Turkey devoted to calculate the optimum slope and orientation angle for example is the one by Murat Kacira In Sanliurfa, Turkey. The study determined the optimum tilt angle between minimum value of 13° in June and 61° in December. In this study the total solar radiation on sloped surface was calculated for different slope and azimuth angles. Also tow mathematic models were used to calculate the optimum tilt angle one of them called liu-Jordan with azimuth angle equal to 0°, and the other called Klein-Theilacker with any value of azimuth angle, and then the comparison between two models was done for calculating the annual solar radiation by using azimuth angle equal to 0° for both models. And an indication of the possibility of using the second model to calculate tilt angle for azimuth angle equal to 0°.

2. MATHEMATICAL MODELS

There are several models that deal with average radiation on the sloped photovoltaic panel, so we shall discuss two of them as shown below.

2.1 Liu and Jordan Model

This is the first model which has been used widely to calculate solar radiation on sloped surface by assuming isotropic sky technique and the orientation Υ angle is equal to 0° in the northern hemisphere, and equal to 180° in the southern hemisphere. The following equations have been used to calculate the optimum title angle and total radiation as shown in Figures (1-5) for a south facing at constant orientation angle [22].

$$H_T = H_b * R_b + \frac{H_D}{2}(1+\cos\beta) + \frac{H_g}{2} * \rho_{g*}(1-\cos\beta) \tag{1}$$

$$R = \frac{H_T}{H} = \left(1-\frac{H_d}{H}\right) * R_b + \frac{H_d}{H} * \left(\frac{1+\cos\beta}{2}\right) + \rho_g * \left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

To estimate the diffuse radiation fraction for monthly-average daily radiation (H_d) Erbs model was used [23]. And monthly global solar radiation on horizontal surfaces (H) was determined from the prediction of worldwide energy resources (power) by NASA [24].

$$\frac{H_d}{H} = 1.391 - 3.560K_T + 4.189K_T^2 - 2.137K_T^3 \tag{3}$$

$$\text{For } \omega_s \le 81.4 \text{ and } 0.3 \le K_T \le 0.8$$

$$\frac{H_d}{H} = 1.311 - 3.022K_T + 3.427K_T^2 - 1.821K_T^3 \quad (4)$$

$$\text{For } \omega_s > 81.4 \text{ and } 0.3 \leq K_T \leq 0.8$$

Since:

ω_s Is sunset hour angle

$$\cos\omega_s = -\tan\emptyset\tan\delta \quad (5)$$

K_T Is the ratio of monthly average global solar radiation on horizontal surface H to monthly average extraterrestrial solar radiation H_o on that, and it is called clearness index.

$$K_T = \frac{H}{H_o} \quad (6)$$

The dependence of extraterrestrial radiation on time of year is given by the equation

$$G_{on} = G_{sc}\left(1 + 0.033\cos\left(\frac{360\, n_{day}}{365}\right)\right) \quad (7)$$

In the above equation, $G_{sc} = 1367\left(\frac{w}{m^2}\right)$ and nday is the day of the year starts from 1st January.

If the solar constant G_{sc} is in watts per square meter, $\overline{H}$o daily joules per square meter per day is given by equation

$$H_o = \frac{24*3600G_{on}}{\pi} * \left(\cos\emptyset\cos\delta\ \sin\omega_s + \frac{\pi\omega_s}{180}\sin\emptyset\sin\delta\right) \quad (8)$$

For $\Upsilon = 0^o$, the ratio of beam average daily radiation on slope surface to that on horizontal surface (R_b) is given by

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\acute{\omega}_s + (\pi/180)\,\acute{\omega}_s\sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\pi/180)\omega s\sin\varphi\sin\delta\,,} \quad (9)$$

Where, $\acute{\omega}_s$ equal to:

$$\acute{\omega}_s = min\begin{bmatrix}\cos^{-1}(-tan\emptyset tan\delta \\ \cos^{-1}(-\tan(\emptyset-\beta)\,tan\delta)\end{bmatrix} \quad (10)$$

Also for Υ = 180° (R_b) is equal to

$$R_b = \frac{cos(\varphi+\beta)\ cos\ \delta\ sin\ \acute{\omega}_s + (\pi/180)\ \acute{\omega}_s\ sin(\varphi+\beta)\ sin\ \delta}{cos\ \varphi\ cos\ \delta\ sin\ \omega_s + (\pi/180)\ \omega_s\ sin\ \varphi\ sin\delta\,,} \quad (11)$$

Where, $\acute{\omega}_s$ equal to:

$$\acute{\omega}_s = min\begin{bmatrix}\cos^{-1}(-tan\emptyset tan\delta \\ \cos^{-1}(-\tan(\emptyset+\beta)\,tan\delta)\end{bmatrix} \quad (12)$$

2.2 Klein and Theilacker Model

Klein and Theilacker investigated an algorithm model to calculate the ratio of total radiation on slope surface to that on horizontal surface (R) for any surface orientation angle γ and all latitudes [2-4]. The equation for (R) is given by following equations:

$$R = D + \frac{\bar{H}_d}{\bar{H}}\left(\frac{1+\cos\beta}{2}\right) + \rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{13}$$

Where

$$D = \begin{cases} max\left(0, G(\omega_{ss}, \omega_{sr})\right) & if\ \omega_{ss} \geq \omega_{sr} \\ max(0, [G(\omega_{ss}, -\omega_s) + G(\omega_s, \omega_{sr})]) & if\ \omega_{sr} > \omega_{ss} \end{cases} \tag{14}$$

$$G(\omega_1, \omega_2) = \frac{1}{2d}\left\{\left(\frac{bA}{2} - \bar{a}B\right)(\omega_1 - \omega_2)\frac{\pi}{180}\right.$$
$$+(\bar{a}A - bB)(\sin\omega_1 - \sin\omega_2) - \bar{a}C(\cos\omega_1 - \cos\omega_2)$$
$$+\left(\frac{bA}{2}\right)(\sin\omega_1\cos\omega_1 - \sin\omega_2\cos\omega_2)$$
$$\left.+\left(\frac{bC}{2}\right)(\sin^2\omega_1 - \sin^2\omega_2)\right\} \tag{15}$$

$$\bar{a} = a - \frac{\bar{H}_d}{H} \tag{16}$$

$$a = 0.409 + 0.5016\sin(\omega_s - \beta) \tag{17}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - \beta) \tag{18}$$

$$d = \sin\omega_s - \left(\frac{\pi * \omega_s}{180}\cos\omega_s\right) \tag{19}$$

$$|\omega_{sr}| = min\left[\omega_s, \cos^{-1}\frac{AB + C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right] \tag{20}$$

$$\omega_{sr} = \begin{cases} -|\omega_{sr}| & if\ (A > 0\ and\ B > 0)\ or\ (A \geq B) \\ +|\omega_{sr}| & otherwise \end{cases} \tag{21}$$

$$|\omega_{ss}| = min\left[\omega_s, \cos^{-1}\frac{AB - C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right] \tag{22}$$

$$\omega_{ss} = \begin{cases} -|\omega_{ss}| & if\ (A > 0\ and\ B > 0)\ or\ (A \geq B) \\ +|\omega_{ss}| & otherwise \end{cases} \tag{23}$$

Where

$$A = \cos\beta + \tan\emptyset\cos\gamma\sin\beta \tag{24}$$

$$B = \cos\omega_s\cos\beta + \tan\delta\sin\beta\cos\gamma \tag{25}$$

$$C = \frac{\sin\beta\sin\gamma}{\cos\emptyset} \tag{26}$$

3. RESULTS AND DISCUSSIONS

3.1 Solar Radiation of Optimum Tilt Angle on an Inclined Surface

As mentioned, before the monthly mean daily values of global solar radiation of Istanbul city was used from the data provide by the prediction of worldwide energy resources (power) by NASA, to calculate the optimum tilt angle and total solar radiation falling on sloped surface towards the south-facing for each month of the year by using Liu and Jordan model. The total solar radiation as shown in Fig. 2 on sloped solar collector was computed for a different tilt angle from 0° to 90° in step by 1°, also the maximum solar radiation for optimum tilt angle was concluded by using a Microsoft Excel spreadsheet. The optimum tilt angle increase in the winter season and it starts decreasing in the spring until it reaches zero in June and then starts to rise in the fall as shown in Figures 4a and 5b, and Fig.5 also the declination angle takes negative value in the winter and fall season, vice versa it takes the positive value in the summer and spring season as shown in Fig. 3. For the winter and fall season $\beta opt > \emptyset$ vice versa $\beta opt < \emptyset$ for summer and spring season. Table 1.and Fig. 1 show the average global daily radiation. Also it shows diffuse, beam, extraterrestrial, total monthly average daily solar radiation, average clear index and optimum tilt angles of the year.

It was found that the highest value was 24.7623 Mj/m^2 day in Jun at βopt = 4° and the lowest value was 7.8421 Mj/m^2 day in December at βopt = 63° as shown in Figures 4b and 5b. The total monthly radiation for all months in the year versus tilt angles that various from 0o to 90° was represented in Fig. 2. Also the optimum tilt angle can be generated depending on declination angle by developed the correlation equations as given below.

$$\beta_{opt.} = 38.701 - 1.3904\,\delta \qquad R^2 = 0.9572 \tag{27}$$

$$\beta_{opt.} = 45.385 - 1.3872\,\delta - 0.0251\,\delta^2 \qquad R^2 = 0.9994 \tag{28}$$

$$\beta_{opt.} = 45.388 - 1.3359\,\delta - 0.025\,\delta^2 - 0.0001\,\delta^3 \qquad R^2 = 0.9996 \tag{29}$$

Equations 27, 28, and 29 represent linear, quadratic and third order polynomials respectively have been estimated to obtain the value of optimum tilt angle βopt. based on declination angle as shown in Fig. 6 the calculations obtained from above equations are given in Table 2. Also Fig. 7 shows the comparison between the calculated values of βopt. with the other values computed from correlation equations and results showed a good approximate with Eq. 29.

Table 1. Declination angle, global, diffuse, beam, extraterrestrial, total monthly average daily solar radiation on tilt surface $\mathrm{Mj/m^2 day}$, average clear index and optimum tilt angles

Month	declination angle	H	H_d	H_b	H_o	H_T	K_T	β_{opt}
Jan.	-20.9170	5.472	2.9135	6.6854	14.5938	9.2337	0.3750	64
Feb.	-12.9546	8.172	3.9926	8.0854	19.9431	11.8969	0.4098	58
Mar.	-2.4177	12.204	5.8184	8.9773	26.9433	15.0015	0.4530	49
Apr.	9.4149	16.56	7.4020	10.0597	34.3219	17.7978	0.4825	31
May.	18.7919	20.844	8.4454	12.4794	39.5959	21.0047	0.5264	11
Jun.	23.0859	23.868	8.7034	15.1646	41.7770	23.8680	0.5713	0
Jul.	21.1837	24.732	8.2228	16.5233	40.6747	24.7623	0.6080	4
Aug.	13.4550	21.312	7.5066	14.4128	36.4046	22.2541	0.5854	22
Sep.	2.2169	16.344	6.2636	12.6227	29.6901	19.4421	0.5505	42
Oct.	-9.5994	9.9	4.7675	8.8420	22.0821	13.6527	0.4483	56
Nov.	-18.9120	6.228	3.1820	7.3066	15.9029	10.2150	0.3916	63
Dec.	-23.0496	4.572	2.6091	5.6018	13.1727	7.8421	0.3471	64

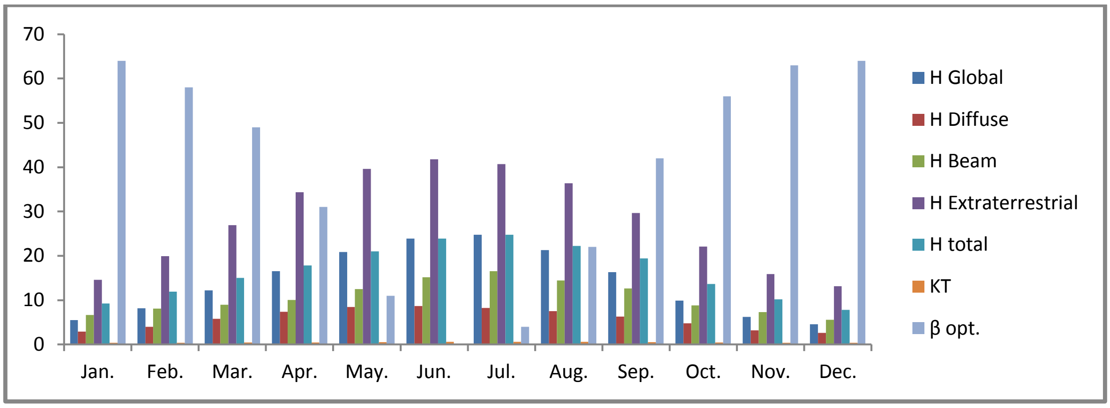


Figure 1. *Global, diffuse, beam, extraterrestrial, total monthly Average daily solar radiation on tilting surface Mj/m^2, clear index and optimum tilts angles*

Table 2. Optimum tilt angle for the developed mathematical models

Months	Jan.	Feb.	Mar.	Apr.	May	Jun	July	Aug.	Sep.	Oct.	Nov.	Dec.
β_{opt}. *Eq27*	67.78	56.71	42.06	25.61	12.57	6.60	9.25	19.99	35.62	52.05	65.00	70.75
β_{opt}. Eq28	63.27	59.05	48.57	30.17	10.59	0.15	4.89	22.27	42.20	56.32	62.51	63.86
β_{opt}. *Eq29*	63.31	58.72	48.47	30.51	10.79	0.01	4.92	22.64	42.30	56.00	62.39	64.12

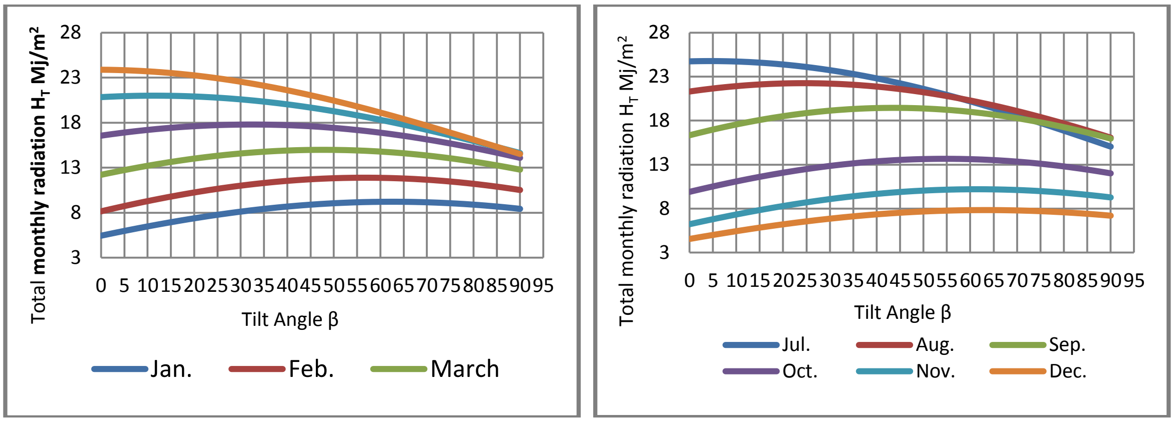
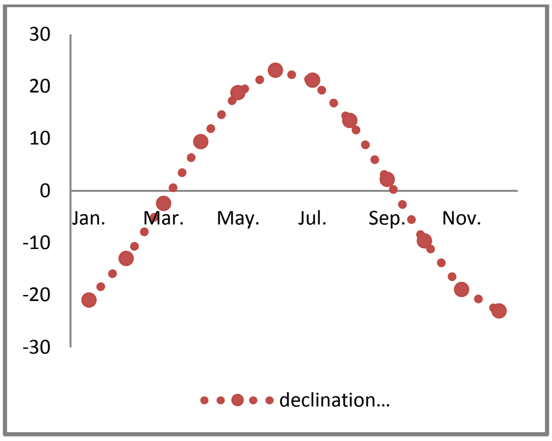


Figure 2. *Total monthly average daily solar radiation for inclined surface at different tilt angle for all months of the year*



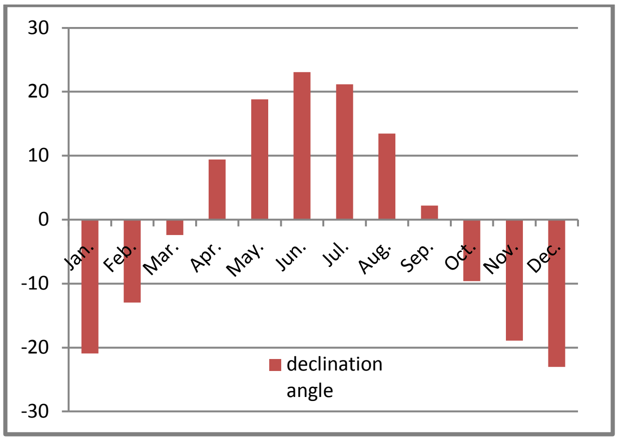
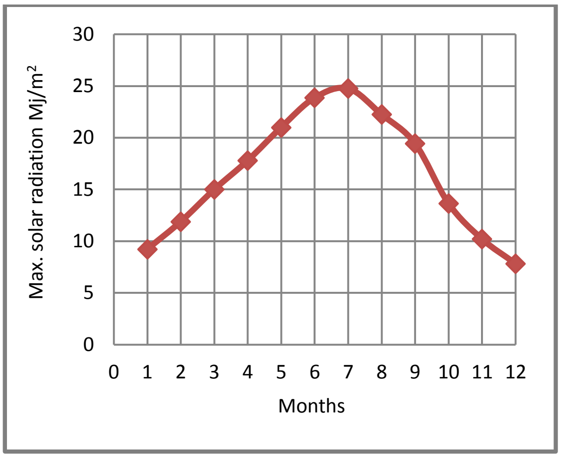
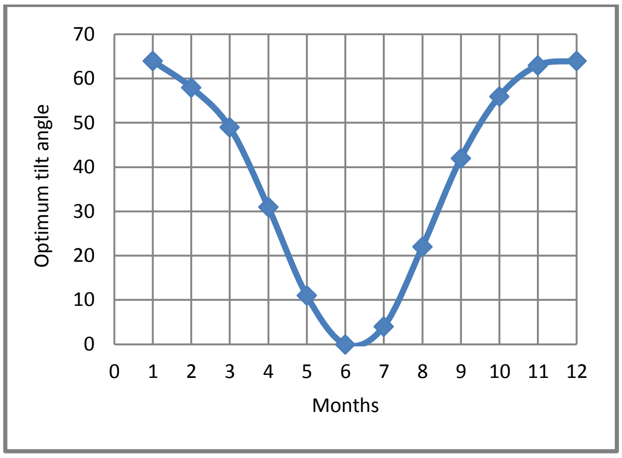


Figure 3. *The value of declination angle for all months of the year*

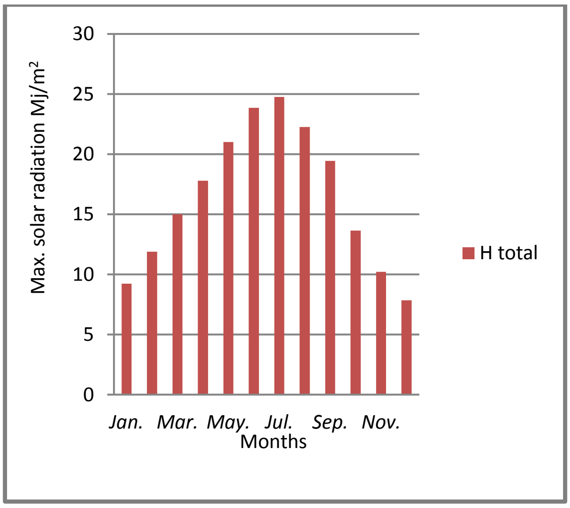


a

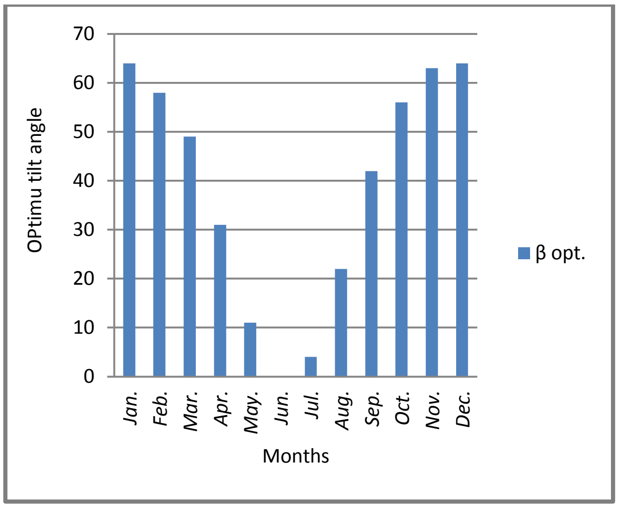


b

Figure 4. *Max. solar radiation (a) and optimum tilt angle (b) for all months of the year*

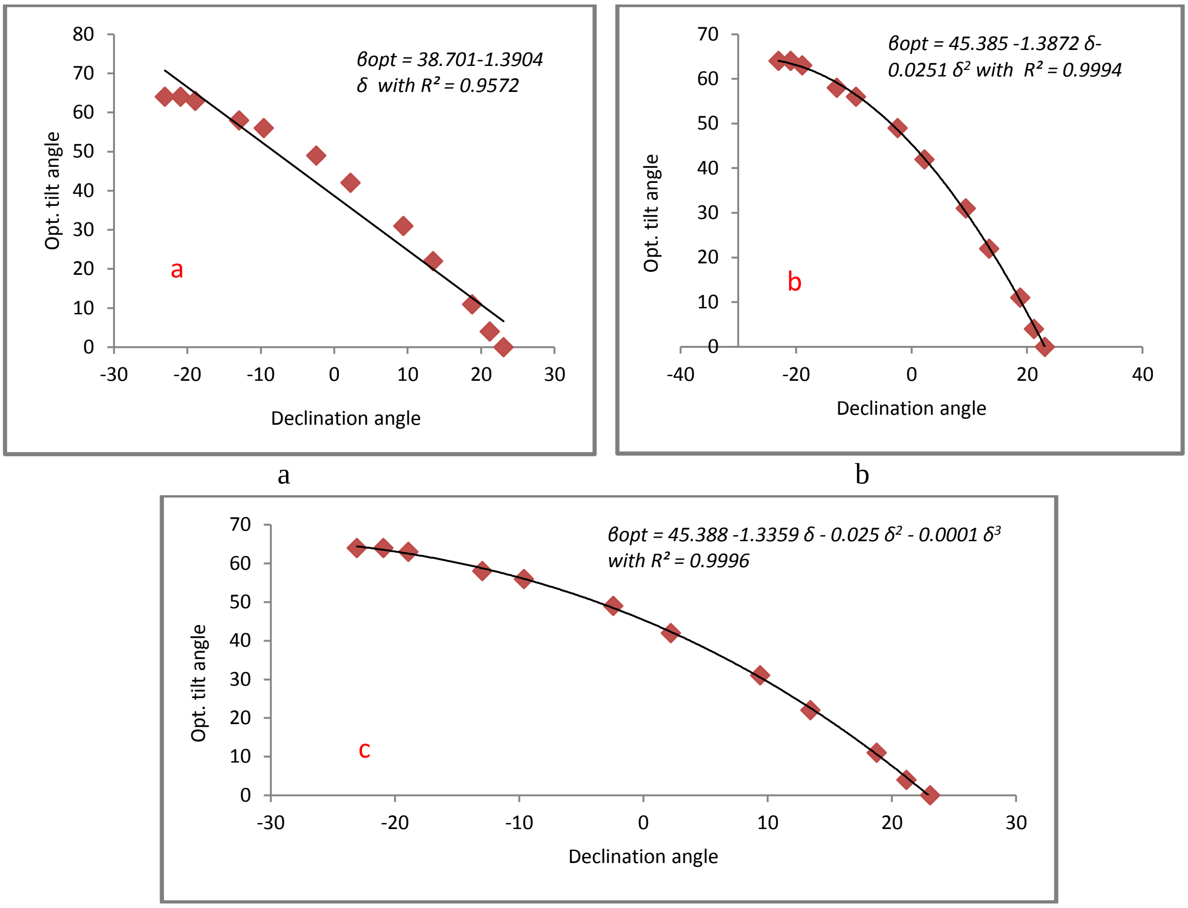


a



b

Figure 5. *Bar chart of max. solar radiation (a) and optimum tilt angle (b) for all months of the year*



c

Figure 6. *General correlations (a) linear, (b) quadratic and (c) third order polynomial*

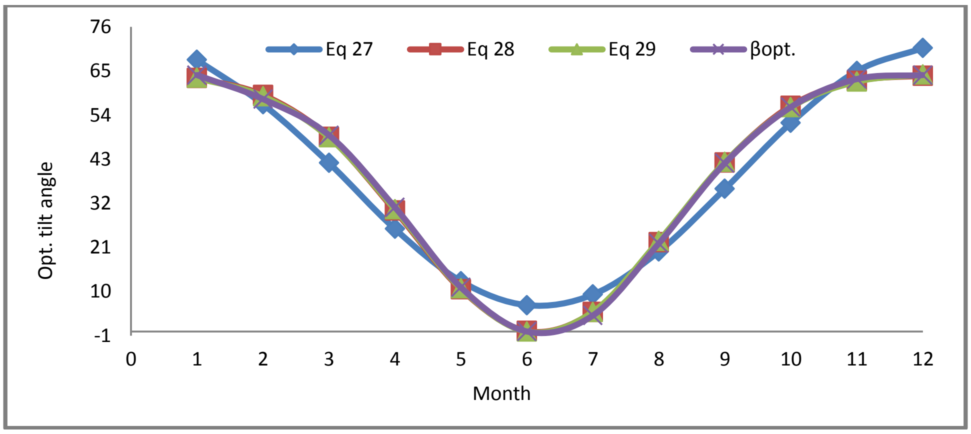


Figure 7. *General correlations (Eq.27) linear, (Eq.28) quadratic and (Eq.29) third order polynomial with βopt*

3.2 Solar Radiation at Optimum Tilt Angle for Different Orientation

In this section the maximum total solar radiation occur at optimum tilt angle for different orientation angle various from 0^o to 90^o by step of 10^o was calculated as shown in Table 3. Because there are a lot of data for calculating maximum total solar radiation for all months in the year, so the details was done only for three months as an example, and other months showed only the Max. H_T and βopt. Figures 8 and 9 shows the total monthly solar radiation at optimum tilt angle for different azimuth angles by using Klein - Theilacker Method. The total solar radiation that calculated by KT method for the months from Jan to Mar. and from Sep. to Dec. has approximately convergent values for β_{opt}. from 0° to 30° at different azimuth angles like, 0°, 10°, 20°, and 30°. On the other hand it has approximately the same values for other months. So, it's not necessary to change azimuth angle, that's mean will be constant at any value from 40° to 80° for months from Apr. to Aug. by adjusting β_{opt}. between 10° to 20° as shown in Table 3. Also it shows from calculations that the max. solar radiation occurs when azimuth angle equal to zero that's mean the pv panel installing towards south - face direction. But as mentioned before the calculations deals with panels that installing with different orientation angles. Fig. 10 and 11 show the variation of total solar radiation and tilt angles along all the months of year. It can be observed that the tilt angle decreases down to 10° at azimuth angle from 10° to 50°, for the months of May, Jun and July. And the max. Solar radiation occurs at tilt angle about 50° for the month of July.

Also for azimuth angle equal to 60°, 70° and 80° the tilt angle equal 10° for the months of (May, Jun, July, Aug.), (Apr., May, Jun, July, Aug.) and (Apr., May, Jun, July, Aug., Sep.) respectively. And the maximum solar radiation occurs at tilt angle. equal about 38°, 30°, 22° for azimuth angle equal to 60°, 70° and 80° respectively. Finally for the azimuth angle equal to 90° the tilt angle will be 0° for all months except Jun that is equal to 10°, and the solar radiation will be maximum in the month of July with tilt angle equal to 0°. The total annual solar radiation, for all months in the year that received by different azimuth and tilt angles were showed in the Table 4 and Fig.12. It is noticed that the annual solar radiation occur at azimuth angle equal 0° that means the pv panels installed in the south face, but as mentioned before the aim of this study deals with different orientation not equal to zero, so the heights annual solar radiation occur at azimuth and tilt angle equal to 10° and 30° respectively. Also it can be noticed from Table 5 that if we used LK method to calculate the total solar radiation by made azimuth angle equal to 0° and changing the tilt angle, the results will be close to the values that obtained from LJ method. Three different correlations linear, quadratic and third order polynomial models based on azimuth angle were developed to calculate optimum tilt angle as shown in Fig.14. The calculations obtained from below equations are given in Table 6.

$$\beta_{opt.} = 33.836 - 0.2564\,\gamma \qquad R^2 = 0.7326 \tag{30}$$

$$\beta_{opt.} = 27.018 + 0.255\,\gamma - 0.0057\,\gamma^2 \qquad R^2 = 0.9629 \tag{31}$$

$$\beta_{opt.} = 28.262 + 0.0275\,\gamma + 0.001\,\gamma^2 - 0.00005\,\gamma^3 \qquad R^2 = 0.9731 \tag{32}$$

The results from above equations show that, by using Eq. 30 the calculated values of annual β_{opt}. did not give accurate values especially for azimuth angle from 30° to 90°. On the other hand by using

Eqs. 31 and 32 the results have a good agreement with annual β_{opt}. especially for Eq. 32. The comparisons of above equations are presented in the Fig. 15.

Table 3. Optimum tilt angle at different orientation for all months

6			$\Upsilon = 10$		$\Upsilon = 20$		$\Upsilon = 30$		$\Upsilon = 40$		$\Upsilon = 50$		$\Upsilon = 60$		$\Upsilon = 70$		$\Upsilon = 80$		$\Upsilon = 90$	
Month	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Jan.	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0	5.820	0
	6.899	10	6.881	10	6.828	10	6.742	10	6.626	10	6.487	10	6.328	10	6.154	10	5.968	10	5.776	10
	7.765	20	7.731	20	7.629	20	7.463	20	7.245	20	6.985	20	6.692	20	6.373	20	6.036	20	5.688	20
	8.382	30	8.334	30	8.189	30	7.954	30	7.647	30	7.287	30	6.884	30	6.451	30	5.997	30	5.535	30
	8.730	40	8.669	40	8.49	40	8.198	40	7.821	40	7.381	40	6.894	40	6.376	40	5.841	40	5.302	40
	8.805	50	8.736	50	8.531	50	8.197	50	7.766	50	7.268	50	6.722	50	6.149	50	5.565	50	4.987	50
	8.621	60	8.547	60	8.326	60	7.965	60	7.499	60	6.963	60	6.384	60	5.783	60	5.181	60	4.596	60
	8.206	70	8.129	70	7.901	70	7.528	70	7.045	70	6.492	70	5.903	70	5.301	70	4.709	70	4.147	70
	7.579	80	7.158	80	7.293	80	6.923	80	6.438	80	5.889	80	5.311	80	4.733	80	4.176	80	3.660	80
	6.838	90	6.765	90	6.547	90	6.19	90	5.719	90	5.190	90	4.645	90	4.113	90	3.614	90	3.163	90
Max.	8.805	50	8.736	50	8.531	50	8.198	40	7.821	40	7.381	40	6.894	40	6.451	30	6.036	20	5.820	0
$\Upsilon = 0$			$\Upsilon = 10$		$\Upsilon = 20$		$\Upsilon = 30$		$\Upsilon = 40$		$\Upsilon = 50$		$\Upsilon = 60$		$\Upsilon = 70$		$\Upsilon = 80$		$\Upsilon = 90$	
Month	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Feb.	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0	8.675	0
	9.847	10	9.828	10	9.769	10	9.676	10	9.552	10	9.401	10	9.226	10	9.033	10	8.825	10	8.609	10
	10.739	20	10.700	20	10.587	20	10.411	20	10.181	20	9.903	20	9.584	20	9.231	20	8.853	20	8.458	20
	11.309	30	11.255	30	11.094	30	10.847	30	10.528	30	10.148	30	9.714	30	9.238	30	8.730	30	8.200	30
	11.541	40	11.473	40	11.273	40	10.968	40	10.580	40	10.120	40	9.602	40	9.038	40	8.440	40	7.821	40
	11.436	50	11.358	50	11.128	50	10.780	50	10.340	50	9.825	50	9.250	50	8.631	50	7.983	50	7.319	50
	11.017	60	10.932	60	10.683	60	10.305	60	9.831	60	9.283	60	8.679	60	8.037	60	7.374	60	6.705	60
	10.321	70	10.233	70	9.975	70	9.581	70	9.090	70	8.530	70	7.923	70	7.289	70	6.644	70	6.005	70
	9.400	80	9.313	80	9.056	80	8.658	80	8.166	80	7.615	80	7.031	80	6.432	80	5.835	80	5.255	80
	8.314	90	8.230	90	7.982	90	7.591	90	7.114	90	6.594	90	6.056	90	5.518	90	4.992	90	4.494	90
Max.	11.541	40	11.473	40	11.273	40	10.968	40	10.580	40	10.148	30	9.714	30	9.238	30	8.853	20	8.675	0
$\Upsilon = 0$			$\Upsilon = 10$		$\Upsilon = 20$		$\Upsilon = 30$		$\Upsilon = 40$		$\Upsilon = 50$		$\Upsilon = 60$		$\Upsilon = 70$		$\Upsilon = 80$		$\Upsilon = 90$	
Month	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
March	12.897	0	12.897	0	12.897	0	12.897	0	12.897	0	12.897	0	12.98	0	12.89	0	12.89	0	12.89	0
	13.935	10	13.918	10	13.868	10	13.787	10	13.678	10	13.542	10	13.38	10	13.20	10	13.01	10	12.80	10
	14.608	20	14.575	20	14.485	20	14.341	20	14.144	20	13.900	20	13.61	20	13.28	20	12.93	20	12.55	20
	14.886	30	14.841	30	14.718	30	14.524	30	14.261	30	13.935	30	13.55	30	13.11	30	12.63	30	12.12	30
	14.764	40	14.708	40	14.560	40	14.327	40	14.016	40	13.632	40	13.18	40	12.67	40	12.11	40	11.50	40
	14.261	50	14.197	50	14.028	50	13.767	50	13.421	50	12.999	50	12.50	50	11.95	50	11.35	50	10.70	50
	13.417	60	13.346	60	13.160	60	12.878	60	12.511	60	12.070	60	11.56	60	11.00	60	10.38	60	9.73	60
	12.287	70	12.211	70	12.012	70	11.715	70	11.339	70	10.897	70	10.39	70	9.85	70	9.26	70	8.64	70
	10.942	80	10.862	80	10.651	80	10.347	80	9.975	80	9.549	80	9.08	80	8.75	80	8.03	80	7.48	80
	9.453	90	9.370	90	9.151	90	8.849	90	8.497	90	8.108	90	7.68	90	7.24	90	6.78	90	6.32	90
Max.	14.886	30	14.841	30	14.718	30	14.524	30	14.261	30	13.935	30	13.61	20	13.28	20	13.01	10	12.89	0
$\Upsilon = 0$			$\Upsilon = 10$		$\Upsilon = 20$		$\Upsilon = 30$		$\Upsilon = 40$		$\Upsilon = 50$		$\Upsilon = 60$		$\Upsilon = 70$		$\Upsilon = 80$		$\Upsilon = 90$	
Apr.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	18.28	20	18.269	20	18.231	20	18.155	20	18.041	20	17.887	20	17.69	20	17.55	10	17.41	10	17.34	0
May	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	21.890	10	21.887	10	21.879	10	21.865	10	21.840	10	21.803	10	21.754	10	21.694	10	21.623	10	21.571	0
Jun	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	24.600	10	24.601	10	24.606	10	24.612	10	24.616	10	24.613	10	24.602	10	24.582	10	24.555	10	24.521	10
July	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	25.718	10	25.717	10	25.716	10	25.714	10	25.703	10	25.682	10	25.649	10	25.604	10	25.548	10	25.485	0
Aug.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	23.078	20	23.071	20	23.049	20	22.994	20	22.895	20	22.752	20	22.594	10	22.463	10	22.315	10	22.224	0
Sep.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	19.481	10	19.446	30	19.325	30	19.117	30	18.825	30	18.451	30	18.103	20	17.710	20	17.374	10	17.222	0
Oct.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	13.298	40	13.226	40	13.021	40	12.716	40	12.350	30	11.958	30	11.507	30	11.048	20	10.648	20	10.497	0
Nov.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	9.766	50	9.691	50	9.469	50	9.138	50	8.737	40	8.269	40	7.755	30	7.289	30	6.849	20	6.623	0
Dec.	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}	H_T	β_{opt}
Max.	7.474	50	7.415	50	7.240	50	*6.955*	*50*	*6.613*	*40*	*6.228*	*40*	*5.804*	*40*	*5.414*	*30*	*5.054*	*20*	*4.866*	*0*

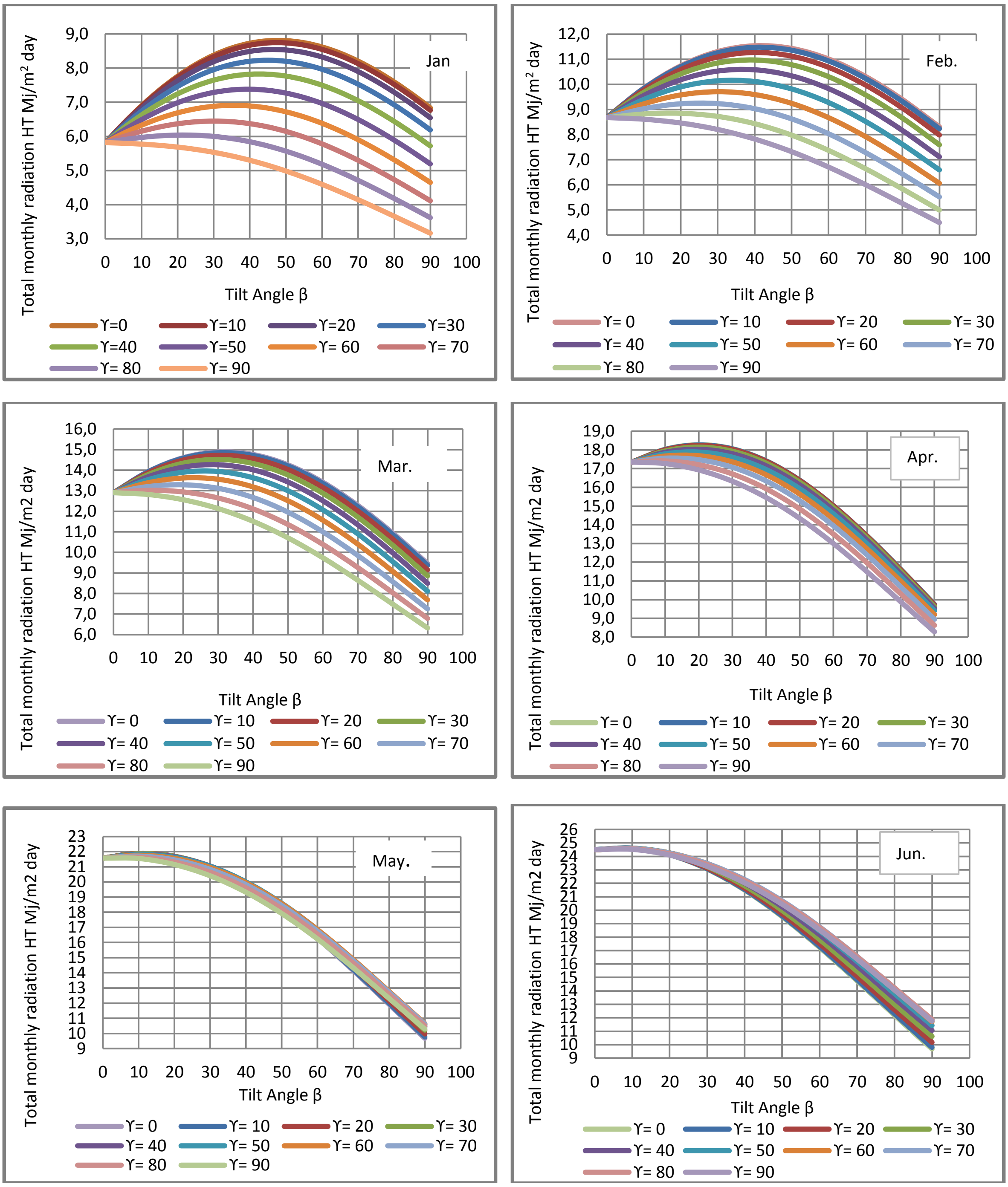


Figure 8. *Total monthly solar radiation for inclined surface at different tilt and azimuth angles for months from Jan. to Jun.*

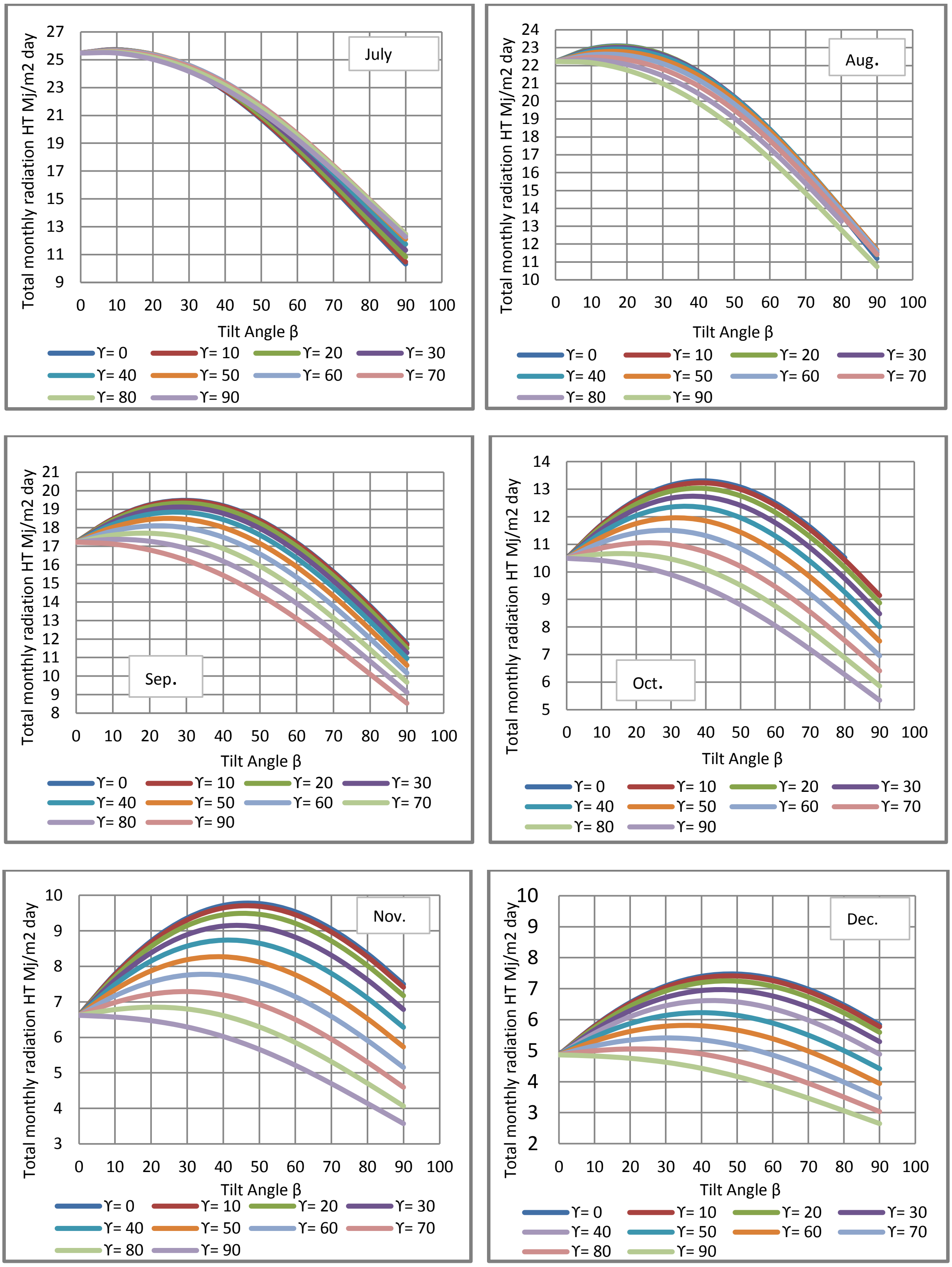


Figure 9. *Total monthly solar radiation for inclined surface at different tilt and azimuth angles for months from Jul. to Dec.*

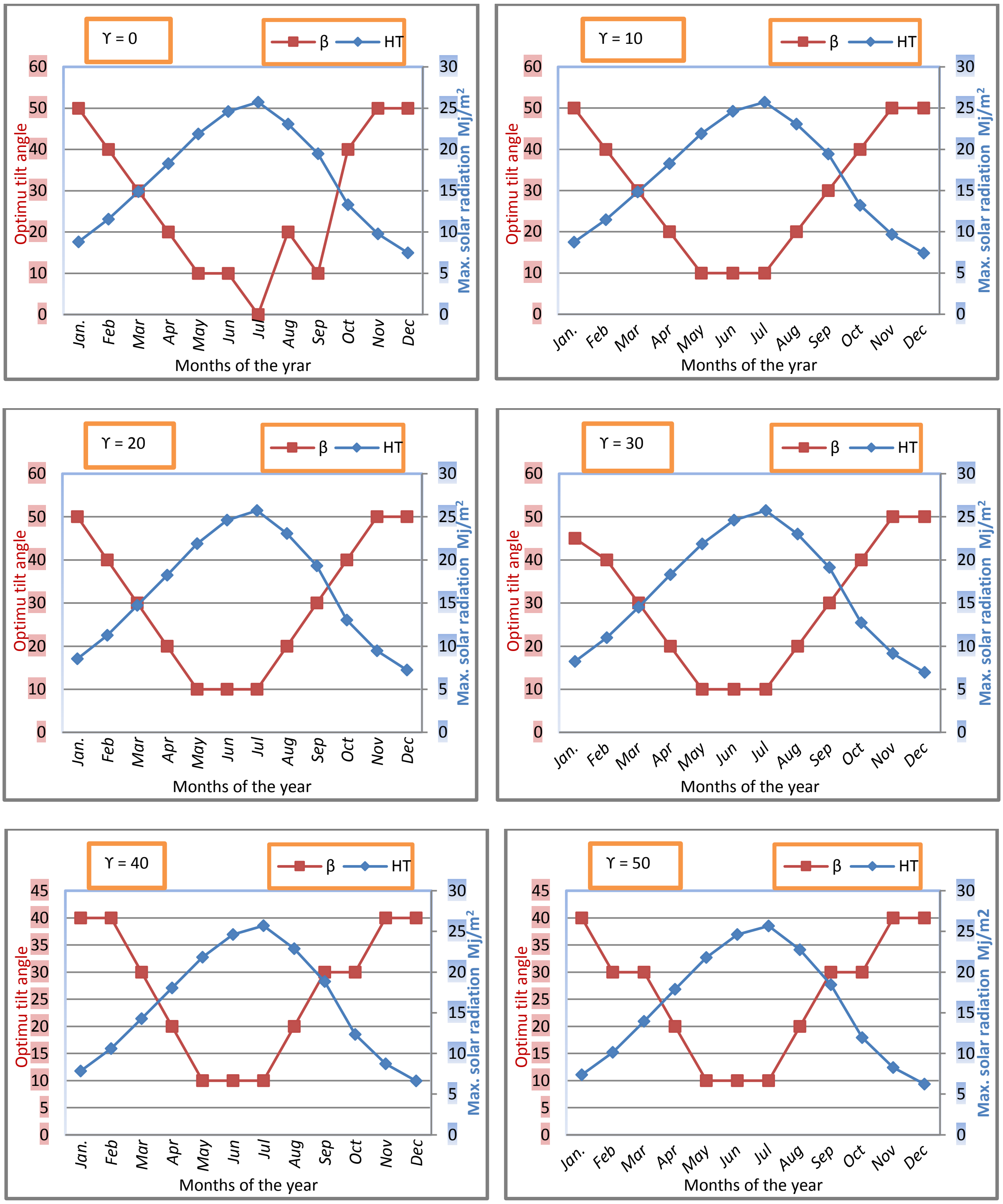


Figure 10. *Max. solar radiation for inclined surface at optimum tilt angles for azimuth angle from 0º to 50º*

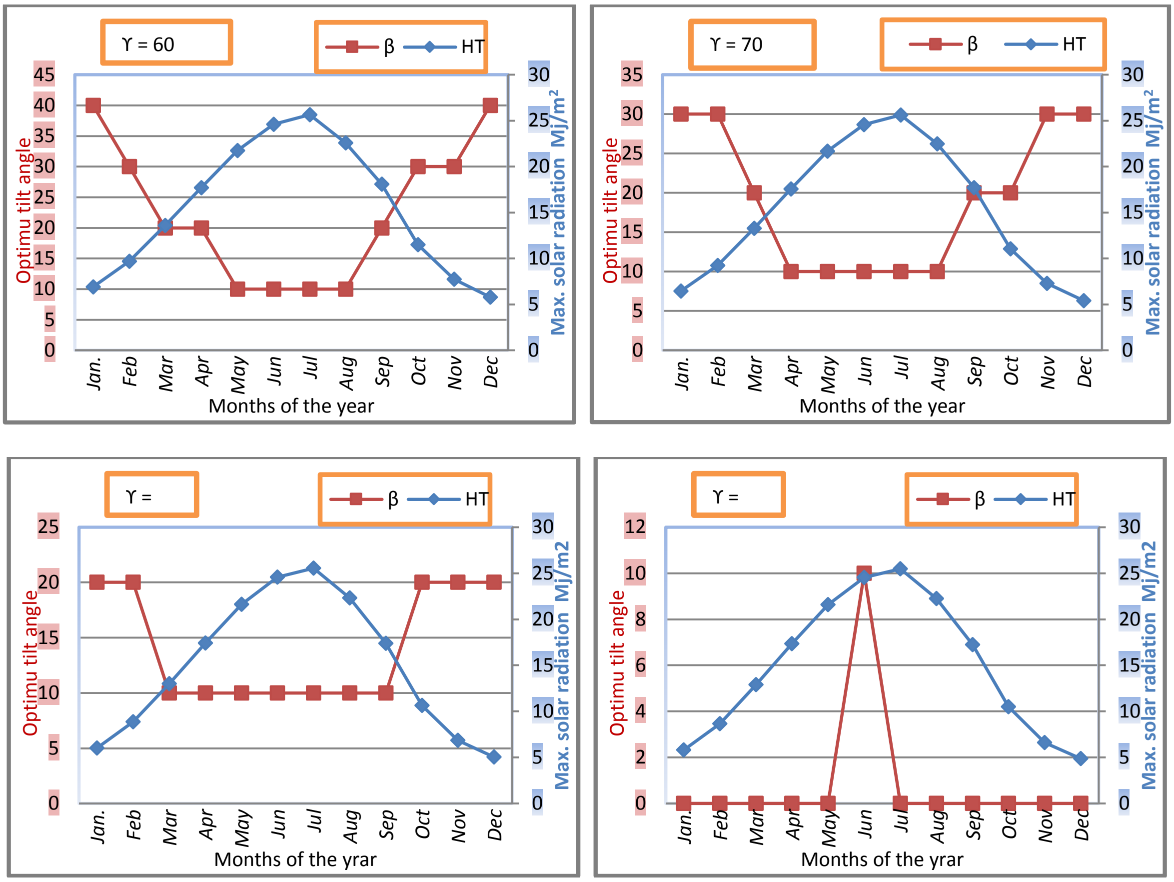
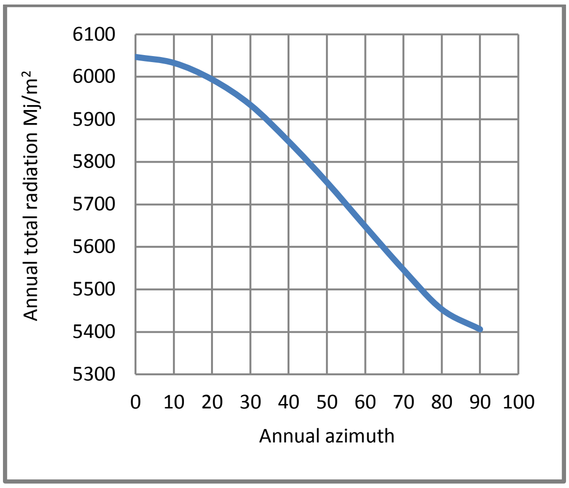
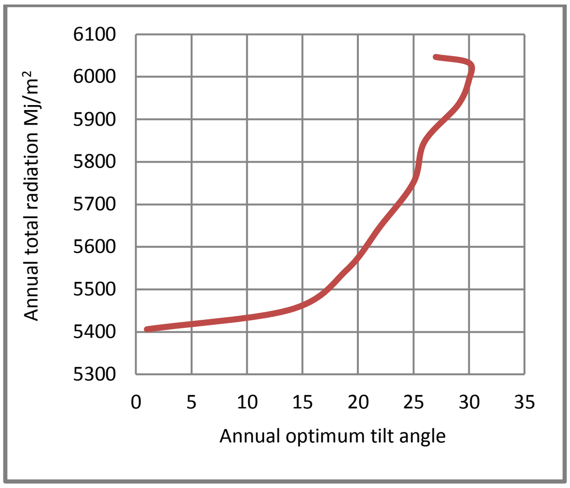


Figure 11. *Max. solar radiation for inclined surface at optimum tilt angles for azimuth angle from 60º to 90º*

Table 4. Yearly optimum tilt angles, annual solar radiation (Mj/m^2) for different orientations

Annual azimuth angle γ degree	Annual β_{opt} degree	Annual Total radiation for different orientation Mj/m^2
0	27	6047
10	30	6033
20	30	5994
30	29	5934
40	26	5848
50	25	5752
60	22	5648
70	19	5546
80	14	5453
90	1	5406



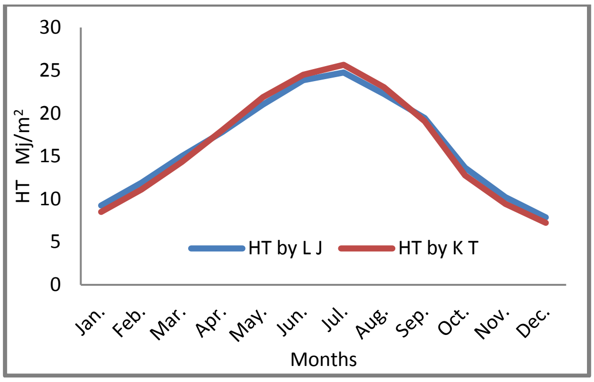


(a) (b)

Figure 12. *annual average total radiation at different orientation (a) with annual optimum tilts angle (b)*

Table 5. HT by Liu - Jordan and Klein -Theilacker method for each month with optimum tilt angle and (ϒ=0)

Month	declination angle	Day of the year	HT by Liu and Jordan	βopt.	HT by Klein and Theilacker
Jan.	-20.917	17	9.2337	64	8.48
Feb.	-12.9546	47	11.8969	58	11.12
Mar.	-2.4177	75	15.0015	49	14.33
Apr.	9.4149	105	17.7978	31	18.02
May.	18.7919	135	21.0047	11	21.89
Jun.	23.0859	162	23.868	0	24.50
Jul.	21.1837	198	24.7623	4	25.65
Aug.	13.455	228	22.2541	22	23.03
Sep.	2.2169	258	19.4421	42	19.08
Oct.	-9.5994	288	13.6527	56	12.77
Nov.	-18.912	318	10.215	63	9.42
Dec.	-23.0496	344	7.8421	64	7.21



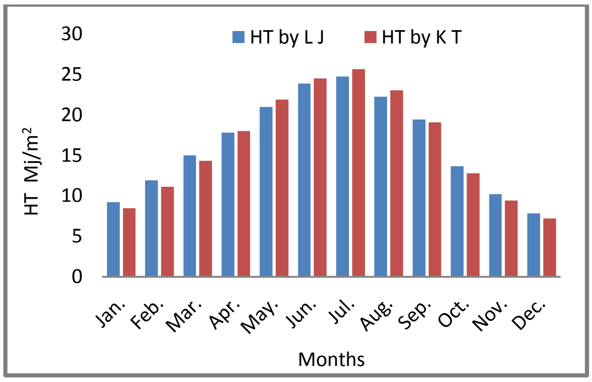


Figure 13. *HT for each month with optimum tilt angle and (ϒ=0)*

Table 6. Annual optimum tilt angle for different azimuth of the developed mathematical models

Annual azimuth angle γ degree	Annual βopt degree	βopt.Eq 30	βopt.Eq 31	βopt.Eq 32
0	27	33.836	27.018	28.262
10	30	36.4	28.998	28.587
20	30	38.964	29.838	28.812
30	29	41.528	29.538	28.637
40	26	44.092	28.098	27.762
50	25	46.656	25.518	25.887
60	22	49.22	21.798	22.712
70	19	51.784	16.938	17.937
80	14	54.348	10.938	11.262
90	1	56.912	3.798	2.387

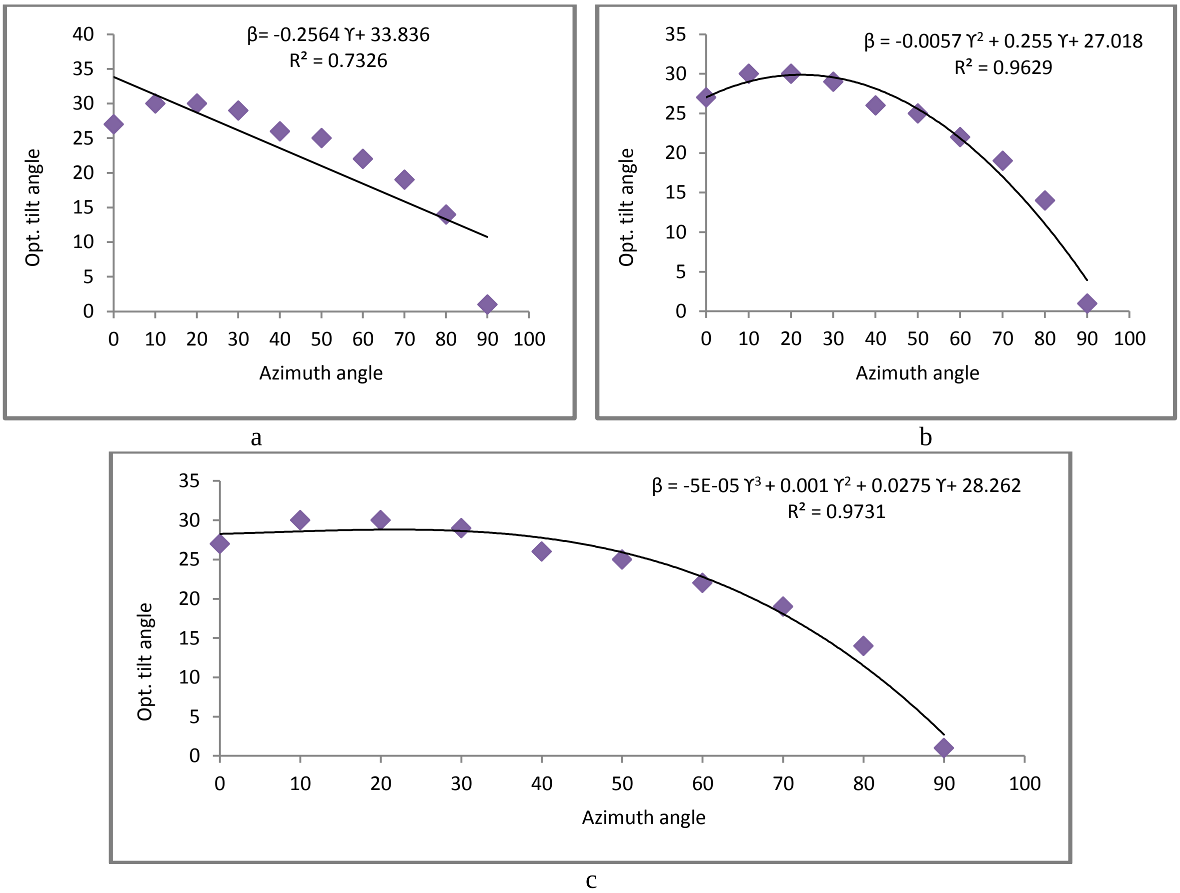


Figure 14. *General correlations (a) linear, (b) quadratic and (c) third order polynomial*

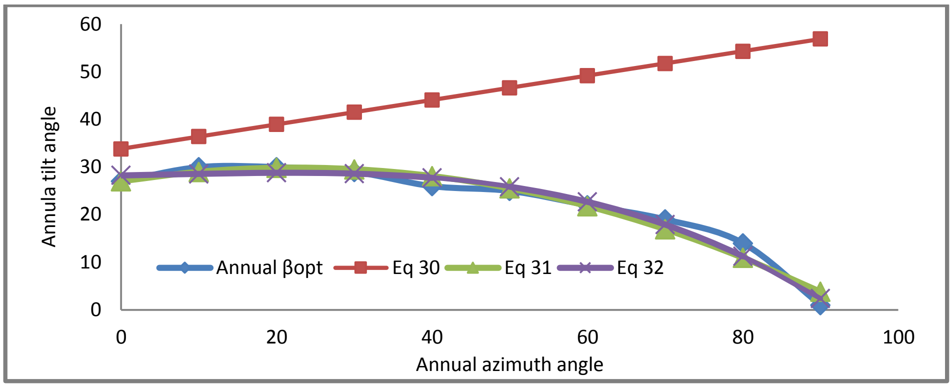


Figure 15. *Annual optimum tilt angle for different azimuth of the developed mathematical models*

4. CONCLUSION

In this study, an estimation of monthly, annual tilt angle of different orientation for Istanbul were performed to calculate the maximum solar radiation and the following conclusions are drawn:

1. The optimum tilt angle for city of Istanbul, Turkey by using Liu-Jordan model increase in the winter season to obtain the appropriate solar radiation, and it starts decreasing in the spring until it reaches zero in June with max. Solar radiation equal to 23.8680 Mj/m^2 and then starts to rise in the fall.
2. For the winter and fall season $\beta_{opt.} > Ø$ vice versa $\beta_{opt.} < Ø$ for summer and spring season, where $Ø$ is the latitude of Istanbul which equal to 41.016.
3. By using Liu-Jordan model the highest value was 24.7623 Mj/m^2 day in Jun at $\beta_{opt.}$ = 4^o and the lowest value was 7.8421 Mj/m^2 day in December at $\beta_{opt.}$ = 63^o
4. The comparison between the calculated values of β_{opt}. and the other values computed from correlation equations showed a good approximate with third order polynomial (Eq. 29).
5. The above conclusions depend on installing the pv panels only towards the south face direction.
6. If it's not possible to installing the pv panel towards the south face ($\Upsilon \neq 0$) because of shading of high building or another reasons the following points will be considered.
7. For azimuth angles change from 10^o to 30^o the optimum tilt angle will be about 30^o to achieve maximum solar radiation for months from Sep. to Dec.
8. For months from April (fall season) to Aug.(summer season) it's not necessary to change azimuth angle, and it can be constant at any value from 40^o to 80^o by adjusting β_{opt}.10^o to 20^o.
9. If the azimuth angle of the panel equal to 90^o the tilt angle will be 0^o for all months except Jun which is equal to 10^o, and the solar radiation will be maximum in the month of July with tilt angle equal to 0^o.
10. The results obtained from linear correlation equation for KT model showed that, the values of annual β_{opt}. did not give accurate values especially for azimuth angle from 30^o to 90^o.

11. By using quadratic and third order polynomial models the results have a good agreement with annual β_{opt}. especially for third order polynomial equation.

CONFLICT OF INTEREST

The author declare that there is no conflict of interest.

DECLARATION OF ETHICAL CODE

In this study, the authors undertake that they comply with all the rules within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" and that they do not take any of the actions under the heading "Actions Contrary to Scientific Research and Publication Ethics" of the relevant directive.

REFERENCES

[1] A. A. Hachicha, I. Al-Sawafta, and Z. Said, "Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions," *Renew. Energy*, vol. 141, pp. 287–297, 2019, doi: 10.1016/j.renene.2019.04.004.

[2] N. Duffie, J. A., Beckman, W. A., & Blair, *Solar Engineering of Thermal Processes*, New York: John Wiley & Sons, 2020.

[3] K. Ulgen, "Optimum tilt angle for solar collectors," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 28, no. 13, pp. 1171–1180, 2006, doi: 10.1080/00908310600584524.

[4] S. A. Klein and J. C. Theilacker, "An Algorithm for Calculating Monthly-Awerage Radiation on Inclined Surfaces," *J. Sol. Energy Eng. Trans. ASME*, vol. 103, no. 1, pp. 29–33, 1981, doi: 10.1115/1.3266201.

[5] S. F. Khahro, K. Tabbassum, S. Talpur, M. B. Alvi, X. Liao, and L. Dong, "Evaluation of solar energy resources by establishing empirical models for diffuse solar radiation on tilted surface and analysis for optimum tilt angle for a prospective location in southern region of Sindh, Pakistan," *Int. J. Electr. Power Energy Syst.*, vol. 64, pp. 1073–1080, 2015, doi: 10.1016/j.ijepes.2014.09.001.

[6] Y. Lv, P. Si, X. Rong, J. Yan, Y. Feng, and X. Zhu, "Determination of optimum tilt angle and orientation for solar collectors based on effective solar heat collection," *Appl. Energy*, vol. 219, pp. 11–19, 2018, doi: 10.1016/j.apenergy.2018.03.014.

[7] M. A. A. Mamun, R. Md Sarkar, M. Parvez, J. Nahar, and M. Sohel Rana, "Determining the optimum tilt angle and orientation for photovoltaic (PV) systems in Bangladesh," 2nd Int. Conf. Electr. Electron. Eng. ICEEE 2017, pp. 1–4, 2018, doi: 10.1109/CEEE.2017.8412910.

[8] G. Hailu and A. S. Fung, "Optimum tilt angle and orientation of photovoltaic thermal system for application in Greater Toronto Area, Canada," *Sustain.*, vol. 11, no. 22, 2019, doi: 10.3390/su11226443.

[9] B. Abdullahi, S. B. Abubakar, N. M. Muhammad, R. K. Al-Dadah, and S. Mahmoud, "Optimum Tilt Angle for Solar Collectors used in Kano, Nigeria Open Access Bala," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 56, no. 1, pp. 31–42, 2019.

[10] S. Heibati, W. Maref, and H. H. Saber, "Developing a model for predicting optimum daily tilt angle of a PV solar system at different geometric, physical and dynamic parameters," *Adv. Build. Energy Res.*, vol. 15, no. 2, pp. 179–198, 2021, doi: 10.1080/17512549.2019.1684366.

[11] T. M. Y. Khan, M. Elahi. M. Soudagar, M. Kanchan, A. Afzal, N. R. Banapurmath, N. Akram, S. D. Mane & K. Shahapurkar, "Optimum location and influence of tilt angle on performance of solar PV panels," *J. Therm. Anal. Calorim.*, vol. 141, no. 1, pp. 511–532, 2020, doi: 10.1007/s10973-019-09089-5.

[12] M. Nfaoui and K. El-Hami, "Optimal tilt angle and orientation for solar photovoltaic arrays: case of Settat city in Morocco," *Int. J. Ambient Energy*, vol. 41, no. 2, pp. 214–223, 2020, doi: 10.1080/01430750.2018.1451375.

[13] R. Abdallah, A. Juaidi, S. Abdel-Fattah, and F. Manzano-Agugliaro, "Estimating the optimum tilt angles for south-facing surfaces in Palestine," *Energies*, vol. 13, no. 3, 2020, doi: 10.3390/en13030623.

[14] M. Oh, J. Y. Kim, B. Kim, C. Y. Yun, C. K. Kim, Y. H. Kang, H. G. Kim "Tolerance angle concept and formula for practical optimal orientation of photovoltaic panels," *Renew. Energy*, vol. 167, pp. 384–394, 2021, doi: 10.1016/j.renene.2020.11.096.

[15] L. Xu, E. Long, J. Wei, Z. Cheng, and H. Zheng, "A new approach to determine the optimum tilt angle and orientation of solar collectors in mountainous areas with high altitude," *Energy*, vol. 237, pp. 121507, 2021, doi: 10.1016/j.energy.2021.121507.

[16] S. Yadav, C. Hachem-Vermette, S. K. Panda, G. N. Tiwari, and S. S. Mohapatra, "Determination of optimum tilt and azimuth angle of BiSPVT system along with its performance due to shadow of adjacent buildings," *Sol. Energy*, vol. 215, pp. 206–219, 2021, doi: 10.1016/j.solener.2020.12.033.

[17] Q. Hassan, M. K. Abbas, A. M. Abdulateef, J. Abulateef, and A. Mohamad, "Assessment the potential solar energy with the models for optimum tilt angles of maximum solar irradiance for Iraq," *Case Stud. Chem. Environ. Eng.*, vol. 4, pp. 100140, 2021, doi: 10.1016/j.cscee.2021.100140.

[18] A. Sharma, M. A. Kallioğlu, A. Awasthi, R. Chauhan, G. Fekete, and T. Singh, "Correlation formulation for optimum tilt angle for maximizing the solar radiation on solar collector in the Western Himalayan region," *Case Stud. Therm. Eng.*, vol. 26, 2021, doi: 10.1016/j.csite.2021.101185.

[19] T. Liu, L. Liu, Y. He, M. Sun, J. Liu, and G. Xu, "A theoretical optimum tilt angle model for solar collectors from keplerian orbit," *Energies*, vol. 14, no. 15, 2021, doi: 10.3390/en14154454.

[20] R. Gardashov, M. Eminov, G. Kara, E. G. Emecen Kara, T. Mammadov, and X. Huseynova, "The optimum daily direction of solar panels in the highlands, derived by an analytical method," *Renew. Sustain. Energy Rev.*, vol. 120, 2020, doi: 10.1016/j.rser.2019.109668.

[21] S. Yadav, S. K. Panda, and C. Hachem-Vermette, "Optimum azimuth and inclination angle of BIPV panel owing to different factors influencing the shadow of adjacent building," *Renew. Energy*, vol. 162, pp. 381–396, 2020, doi: 10.1016/j.renene.2020.08.018.

[22] B. Y. H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation," *Sol. Energy*, vol. 4, no. 3, pp. 1–19, 1960, doi: 10.1016/0038-092X(60)90062-1.

[23] D. G. Erbs, S. A. Klein, and J. A. Duffie, "Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation," *Sol. Energy*, vol. 28, no. 4, pp. 293–302, 1982, doi: 10.1016/0038-092X(82)90302-4.

[24] NASA, "Surface meteorology and Solar Energy", (2014). [Online]. Available: https://ntrs.nasa.gov.