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SURFACE ORIENTATIONS AND ENERGY POLICY FOR SOLAR MODULE APPLICATIONS IN DHAKA, BANGLADESH

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Abstract-Incident solar irradiation of photovoltaic collector is affected by tilt and az imuth angles. This study introduces a new mathematical model for calculating the optimum tilt and azimuth angles for Solar Collector Applications in Bangladesh using the second derivative test to find the maxima of a single variable on yearly, seasonal and monthly bases. The result shows optimum tilt angles for solar applications. This study finds that optimum tilt angle is 30 degree in Dhaka, greater than the local latitude of $\varphi = 23.7$ degree for grid connected PV system to obtain maximum yearly energy generation where energy increment rate is 8.72% than horizontal radiation and 0.21% than latitude oriented radiation. Seasonal optimum tilt is found as 47 degree for months October-February and 10 degree for months March-September, energy produced is 4.36% more than that of annual optimum tilt. Also monthly optimum tilt energy is 5.04% more than annual fixed tilt.

Keywords: Energy policy, tilted radiation, optimum tilt, surface orientation, solar module, maximum power, tilt angle.

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1. INTRODUCTION

The techniques for estimating typical solar radiation on surfaces of various directions can be used to show the special effects of slope and azimuth angle on total energy received on a surface on a monthly, seasonal or annual basis. The surface direction leading to highest output of a solar energy structure may be fairly different from the orientation leading to maximum incident energy.

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For solar energy purposes, the most favorable orientation is usually recommended to be south facing in the northern hemisphere and the optimum tilt depends simply on the local latitude. According to Duffie and Beckman [1] optimum tilt is within the range $(\varphi \pm 15\,deg) \pm 15deg$ and another author Lewis [2] suggested it as $\beta_{opt} = (\varphi \pm 8\,deg)$, where φ is the local latitude.Christensen and Barker [4] analyzed over surface tilt and azimuth angles and found a diversity of these with a significant range without considerably dropping the amount of yearly incident irradiation.

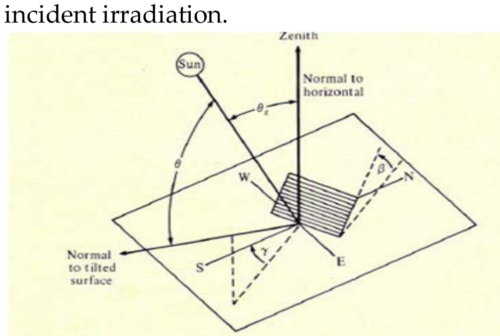

Figure 1: zenith angle, slope, incident angle, surface azimuth angle and solar azimuth angle for a tilted surface [1].

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2. THEORETICAL CONSIDERATIONS

The top up atmospheric irradiation on a horizontal surface H_0 is a function of latitude and independent of other locational parameters. When the radiation is passed through the earth's atmosphere, it is further adapted by processes of diffusion and inclusion due to the existence of cloud and other atmospheric element.

The top up atmosphere solar radiation on a horizontal surface is measured from the following equation [1]:

$$H_0 = \frac{24 \times 3600 \times I_{sc}}{\pi}\left(1 + 0.033 cos\left(360\frac{d}{365}\right)\right) \quad (1)$$

Where, $I_{sc} = 1367 Wm^{-2}$ is the solar constant and H_0 is in Jm^{-2} [1].

d is the day number, ϕ is the local latitude, δ is the declination given by

$$\delta = 23.45\, sin\left(360\frac{284 + d}{365}\right) \quad (2)$$

and ω is the sunset hour angle given by

$$\omega = cos^{-1}(-tan\phi tan\delta) \quad (3)$$

3. BEAM RADIATION ON HORIZONTAL SURFACE

The ratio of beam radiation on the tilted surface to that on a horizontal surface at any time can be calculated exactly from the following equation. Figure 3 indicates the angle of incidence of beam radiation on the horizontal and tilted surfaces [1].

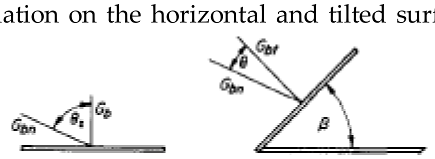

Figure 2: beam radiation on horizontal and tilted surfaces [1].

The ratio is given by

$$R_b = \frac{G_{b,T}}{G_b} = \frac{G_{b,n}\, cos\theta}{G_{b,n}\, cos\theta_z} = \frac{cos\theta}{cos\theta_z} \quad (4)$$

where,

$$cos\theta = sin\delta\, sin\varphi\, cos\beta - sin\delta\, cos\varphi\, sin\beta\, cos\gamma + cos\delta\, cos\varphi\, cos\beta\, cos\omega + cos\delta\, sin\varphi\, sin\beta\, cos\gamma\, cos\omega + cos\delta\, sin\beta\, sin\gamma\, sin\omega$$

and $cos\theta_z = cos\varphi\, cos\delta\, cos\omega + sin\varphi\, sin\delta$

The best azimuth angle for solar collectors is usually 0^0 in the northern hemisphere. Thus, upon simplification equation (4) reduces to

$$R_b = \frac{\cos(\varphi - \beta)\ cos\delta\, cos\omega + \sin(\varphi - \beta)\ sin\delta}{cos\varphi\, cos\delta\, cos\omega + sin\varphi\, sin\delta} \quad (5)$$

But according to Liu and Jordan [10] $\overline{R_b}$ is calculated from

$$\overline{R_b} = \frac{cos(\varphi - \beta)cos\delta sin\omega_s + \left(\pi/_{180}\right)\omega_s sin(\varphi - \beta)sin\delta}{cos\varphi cos\delta sin\omega_s + \left(\pi/_{180}\right)\omega_s sin\varphi sin\delta} \quad (6)$$

Where, ω_s denotes the sunset hour angle and is taken to the smaller value from

$$\omega_s = cos^{-1}(-tan\varphi tan\delta)$$
$$\omega_s = cos^{-1}(-tan(\varphi - \beta)tan\delta) \quad (7)$$

4. METHODOLOGY FOR THE OPTIMUM TILT:

We calculate the tilted radiation for known total horizontal radiation. The direction from which diffuse radiation is received, i.e., its flow over the sky ground, is a function of mostly unpredictable conditions of cloudiness and atmospheric clarity.

The tilted radiation is the sum of radiation streams including beam radiation, the three parts of diffuse radiative flux of the sky, and radiation reflected from the different surfaces on the tilted surface. The total radiation on this surface can be written as

$$\overline{H_T} = \overline{H}\left(1 - \frac{\overline{H_d}}{\overline{H}}\right)\overline{R_b} + \overline{H_d}\left(\frac{1 + cos\beta}{2}\right) + \overline{H}\rho_g\left(\frac{1 - cos\beta}{2}\right) \quad (8)$$

Where, $\overline{H_d}$ is the monthly average daily diffuse radiation, $\overline{R_b}$ is the monthly average daily geometric factor for beam radiation, β is the slope of the surface and ρ_g is the diffuse reflectance for the total solar radiation of the location.The surface view factor to the sky is $\left(\frac{1+cos\beta}{2}\right)$ and the surface view factor to the ground $\left(\frac{1-cos\beta}{2}\right)$

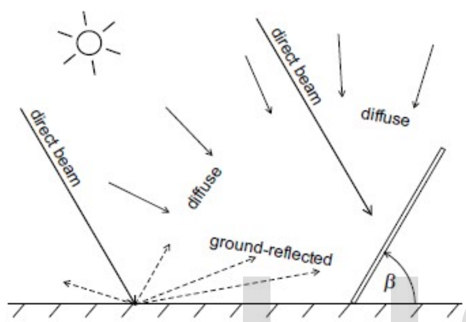

Figure 3: Beam, diffuse and reflected solar radiation on tilted surface [1]

The first step to calculate the average monthly tilted solar radiation is to calculate R_b using equation (6) and the relationship H_d/H from the measured data or using any of the correlation models. Equations considered in this study for these correlations are as follows [9]:

For $\omega_s \leq 81.4^0$ and $0.3 \leq \overline{K}_T \leq 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.391 - 3.560\overline{K}_T + 4.189\overline{K}_T^{\ 2} - 2.137\overline{K}_T^{\ 3} \quad (9)$$

And for $\omega_s > 81.4^0$ and $0.3 \leq \overline{K}_T \leq 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.311 - 3.022\overline{K}_T + 3.427\overline{K}_T^{\ 2} - 1.821\overline{K}_T^{\ 3} \quad (10)$$

For known R_b and H_d/H ratio, monthly average daily radiation on tilted surface was calculated.

For a fixed orientation, the optimum tilt angle can be found by solving the following equation for β

$$\frac{d}{d\beta}(\overline{H_T}) = 0 \quad (11)$$

Now, since diffuse and ground reflected parts are negligible, the above equation turns into

$$\frac{d}{d\beta}(\overline{R_b}) = 0 \quad (12)$$

$$\Rightarrow \frac{sin(\varphi - \beta)cos\delta sin\omega_s - (\pi/180)\omega_s\, cos(\varphi - \beta)sin\delta}{cos\varphi cos\delta sin\omega_s + (\pi/180)\omega_s sin\varphi sin\delta} = 0$$

$$\Rightarrow \beta = \varphi - tan^{-1}\left(\frac{(\pi/180)\omega_s\, sin\delta}{cos\delta\, sin\omega_s}\right) \quad (13)$$

For fixed values of φ, ω_s and δ for a particular month at a specific location, the optimum tilt angle is easily determined.

5. RESULTS AND DISCUSSION

TOTAL ENERGY RECEIVED ON ANNUAL BASIS:

For shaping optimum orientation it is important to find out local optimum tilt angle. The maximum energy obtained at south facing azimuth angle with 30 degree slope ($\varphi + 7$ deg) as shown in figure 6. The solar collectors placed with optimum slope can generate 8.76% more power than horizontally placed collectors. Compared with slope equal to latitude, the one with optimum slope can generate 0.21% more power. Upon determined the tilt factors by using equation (7), figure 5 presents graphically for the months for different orientations.

With an observation and theoretical consideration it is concluded that the yearly collected solar radiation reduces sharply when the slopes exceed 40 deg. Figure 6 shows bar charts of annual total tilted radiation for different tilts, where it has been found that for tilt equal to 30 degree the annual total solar radiation is highest.

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Table 1: Tilt factor and monthly average tilted radiation for latitude oriented and optimum oriented for annual optimum power output

Month	Tilt factor R_b $(\beta = \varphi)$	Monthly average Tilted radiation (MJ/m^2)	Tilt factor R_b $(\beta = 30^0)$	Monthly average Tilted radiation (MJ/m^2)
Jan	1.43	20.71	1.51	21.62
Feb	1.29	21.31	1.33	21.75
Mar	1.12	21.66	1.13	21.72
Apr	0.98	20.29	0.95	19.79
May	0.88	17.61	0.83	16.95
Jun	0.84	14.88	0.78	14.29
Jul	0.86	14.06	0.81	13.57
Aug	0.94	14.77	0.9	14.34
Sep	1.06	14.63	1.05	14.43
Oct	1.23	17.56	1.26	17.74
Nov	1.39	19.59	1.46	20.29
Dec	1.48	20.69	1.57	21.71
Annual total		6617.16		6630.86

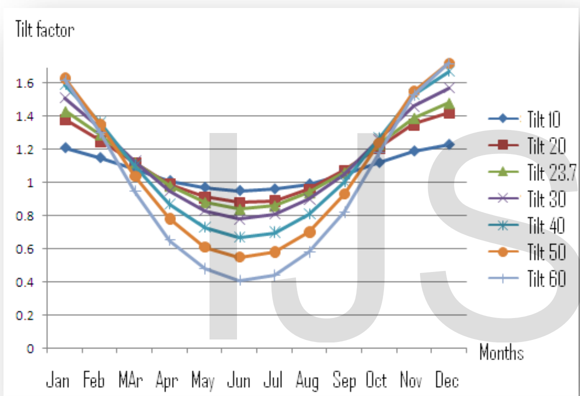

Figure 4: Tilt factor vs months of year for fixed slope

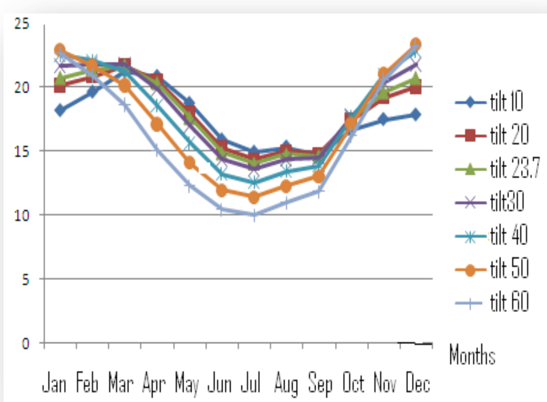

Figure 5: solar radiation (MJ/m^2) vs months for fixed orientation throughout the year

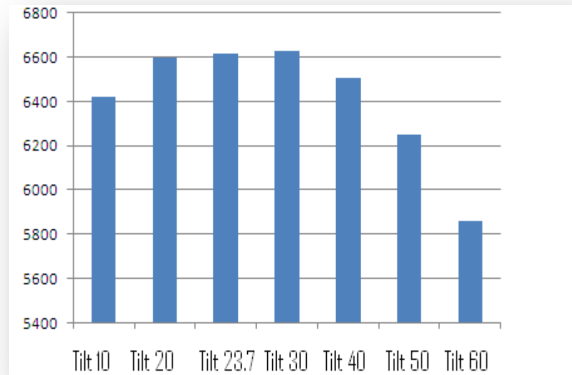

Figure 6: Annual total solar radiation (MJ/m^2) vs tilt

Total energy received on seasonal basis:

If we divide the whole year into two seasons on the basis of high tilt factor and low tilt factor then we get an optimum tilt angle as 47 degree for the months October-February and 10 degree for the months March-September and energy obtained in this case is 4.36% more than the energy obtained for annual optimum tilt.

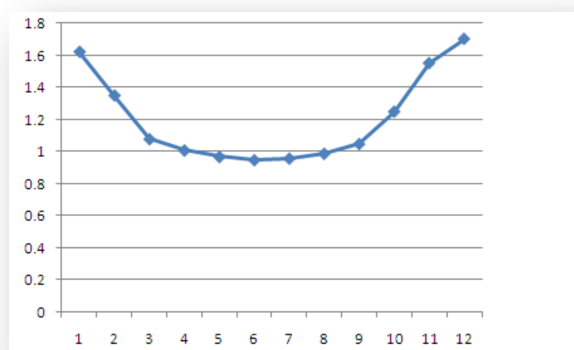

Figure 7: Tilt factor vs months of year for variable slope (Tilt for Mar-Sep is 10 degree and Oct-Feb is 47 degree)

Figure 7 shows the tilt factor for seasonal tilt where 10 degree is for the months through March to September and 47 degree for the months through October to February.

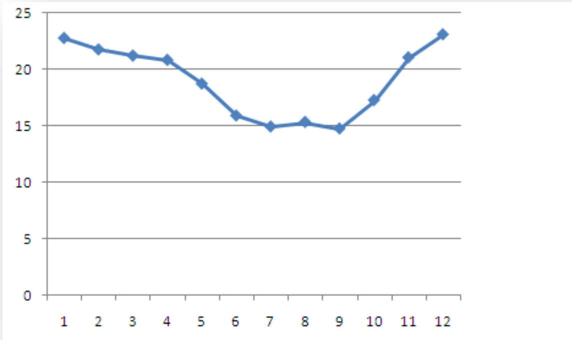

Figure 8: Tilted Solar radiation (MJ/m^2) vs months of year for variable slope (Tilt for Mar-Sep is 10 degree and Oct-Feb is 47 degree)

Total energy received on monthly basis:

Monthly optimum tilt:

Monthly basis optimum tilt can be found by using equation (13) for fixed values of φ, ω_s and δ for a particular month at a specific location. Energy produced at Dhaka in this case is 5.05% more than energy obtained for annual optimum tilt and 0.65% more than energy obtained for seasonal optimum tilt. Figure 9 shows the optimum tilt angles for different months throughout the year. Figure 10 shows the optimum tilt factor for the months of the year.

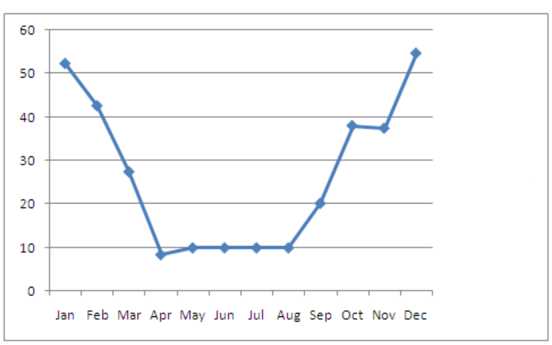

Figure 9: Optimum tilt for different months of the year

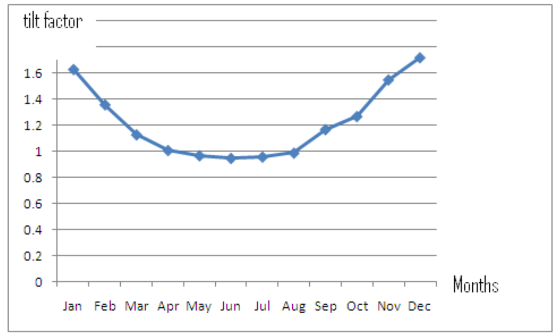

Figure 10: Tilt factors vs months for monthly optimum tilt

Table 2: Tilt factor and monthly average tilted radiation for seasonal optimum and monthly optimum power output

Month	Seasonal Tilt factor R_b	Tilted radiation (MJ/m^2)	Monthly Tilt factor R_b	Tilted radiation (MJ/m^2)
Jan	1.62	22.77	1.63	22.86
Feb	1.35	21.76	1.36	22.01
Mar	1.08	21.21	1.13	21.72
Apr	1.01	20.83	1.01	20.83
May	0.97	18.72	0.97	18.73
Jun	0.95	15.89	0.95	15.89
Jul	0.96	14.92	0.96	14.92
Aug	0.99	15.32	0.99	15.328
Sep	1.05	14.74	1.17	14.762
Oct	1.25	17.27	1.27	17.74
Nov	1.55	21.06	1.55	21.01
Dec	1.7	23.10	1.72	23.31
Annual total		6919.11		6964.31

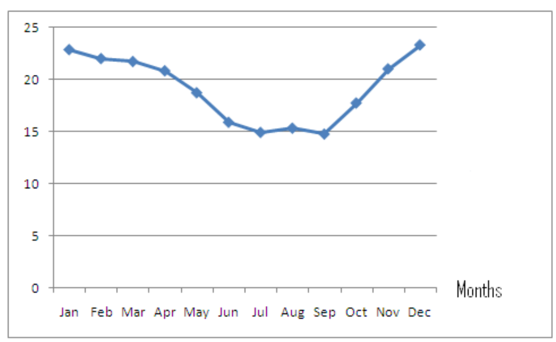

Figure 11: Tilted Solar radiation (MJ/m^2) vs months of year for monthly basis tracking

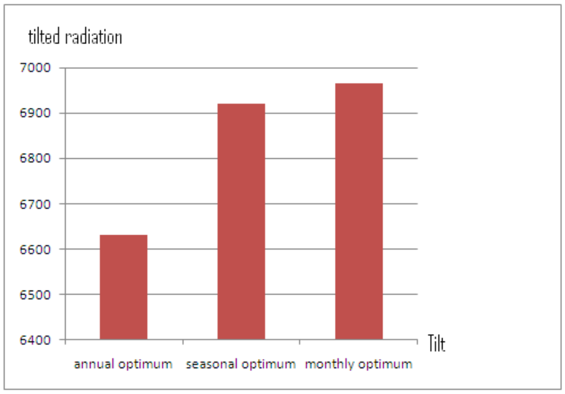

Figure 12: energy (MJ/m^2) output for three different orientations

It is seen from figure 12 that maximum power is generated for monthly optimum tilt. Seasonal tilt energy output is nearly equal to that of monthly output.

Table 3: Energy increment rate at different orientations

Surface orientation	Annual total Energy (MJ/m^2)	Increment rate than horizontal	Increment rate than latitude oriented	Increment rate than annual oriented
Horizontal (tilt=0)	6097.98			
Latitude oriented (tilt=23.7)	6617.16	8.5%		
Annual optimum (tilt=30)	6630.86	8.72%	0.21%	
Seasonal optimum	6919.11	13.46%	4.56%	4.36%
Monthly optimum	6964.31	14.2%	5.25%	5.04%

Table 3 shows the increment rate of power produced over different types of surface orientations for annual fixed, seasonal fixed and monthly variations. Annual optimum ($\beta = 30^0$) energy is increased at a rate of 8.72% than horizontal orientation and 0.21% more energy is obtained than latitude oriented surfaces. Seasonal ($\beta = 10^0$ for Mar-Sep and 47^0 for Oct-Feb) optimum energy is increased 4.36% than annual optimum energy obtained. For monthly variation of surface orientation, energy is 5.25% more than latitude oriented and 5.04% more than annual optimum output.

6. CONCLUSION

The efficiency and performance of solar collectors and Building–Integrated Photovoltaic systems depend on the collector's orientation. The Photovoltaic collectors should be tilted in an appropriate manner to obtain the utmost radiation. In this study it is found that optimum tilt angle is 30 degree in Dhaka, a little bit higher than the local latitude of $\varphi = 23.7\,deg$ for grid connected PV system to obtain maximum yearly energy generation. Seasonal optimum tilt reaches to 47 degree for months (October-February) and 10 degree for months (March - September). If the slopes could be adjusted monthly, the power efficiency would likely be much better.

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