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Optimum Tilt Angle for Solar Panel in Pune

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ABSTRACT - The main aim of this paper is to find the optimum tilt angle for a solar panel in Pune. This is achieved by maximizing the annual radiation and finding the corresponding slope for it. This work presents a simple numerical model, based on a spreadsheet, to optimize solar panel tilt angle for given panel and solar azimuth angle. First beam, diffused and reflected radiations on a titled surface are calculated independently for a given azimuthal angle in a day. Then then it is converted to monthly radiation which are then added to obtain the annual radiation. Then by implementing spreadsheet's solver, the tilt angle to yield maximum annual solar irradiation per square area of panel is evaluated.

Keywords- incident angle, tilt angle, beam radiation, diffused radiation, reflected radiation, annual solar radiation for tilted surface

I. INTRODUCTION

Renewable energy has become a very important source of energy in the current world, as the conventional sources of energy are on the brink of extinction as well as extremely polluting. There are multiple renewable energy sources but very few could actually meet the current world demand for energy, solar energy being prominent among them.

The sun is the only start of our solar system located at its centre. The earth and the other planets orbit the sun. Energy from sun the in form of solar radiation supports almost all life on earth via photosynthesis and drives the earth's climate and weather. Solar energy is a very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8× 〖10〗 ^11 MW [1], which is many thousand times than the present consumption rate on earth of all commercial energy resources. Thus, theoretically, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources.

Presently the conversion rate of solar energy to usable energy is 15%-30% which is very low. In order to aid the current method of solar energy collection the slope of the solar panels must be such that the solar radiation fall normal to the surface so as to achieve maximum energy collection.

Due to the importance of this problem a number of research work on determining the optimum solar panel tilt angles have been published. The most prominent among them is work by Yin-Ping Chang uses combination of sequential neural-network approximation and orthogonal arrays (SNAOA) to determine the tilt angle for photovoltaic (PV) modules. In this study, seven Taiwanese areas were selected for analysis. The sun's position at any time and location was predicted by the mathematical procedure of Julian calendar; then, the solar irradiation was obtained at each site under a clear sky. Chen et al. used the Genetic Algorithm (GA) and the Simulated-Annealing (SA) method to determine the optimum tilt angle for the fixed solar-cell panels. They utilized the climatic data with GA and SA to calculate the optimum installation angle of the solar-cell panel for different locations in Taiwan. They found that the best monthly and annual installation angles obtained by computer simulations are very close to the data obtained by experiment.[2]

The current work uses a model programmed into a spreadsheet. It contains the relation between the tilt angle and annual radiation per unit area of that panel, then by using Excel Solver the radiation is maximized by varying the tilt angle. The model is then used to determine the optimum tilt angle for Pune.

II. ANALYSIS

Solar radiation is received at the earth's surface in an attenuated form because it is subjected to the mechanisms of absorption and scattering as it passes through the earth's atmosphere (fig.1). Absorption occurs primarily because of the presence of ozone and water vapour in the atmosphere, and to a lesser extent due to other gases (like CO_2, NO_2, CO, O_2 and CH_4) and particulate matter[2]. It results in an increase in the internal energy of the atmosphere. On the other hand, scattering occurs due to all gaseous molecules as well as particulate matter in the atmosphere. The scattered radiation is redistributed in all directions, some going back into space and some reaching the surface.

The atmosphere at any location on the earth's surface is often classified into two broad types-an atmosphere without clouds and atmosphere with clouds. In the former case, the sky is cloudless everywhere, while in the latter, the sky is partly or fully covered by clouds. The mechanism of scattering and absorption is similar for both types of atmosphere. However it is obvious that less attenuation takes place in a cloudless sky. Consequently maximum radiation is received on the earth's surface under the conditions of cloudless sky.

Solar radiation received at the earth's surface without change of directions that is in line with the sun, is called as beam or direct radiation[1]. The radiation received at the earth's surface from all parts of the sky's hemisphere (after being subjected to scattering in the atmosphere) is called as diffused radiation. The sum of the beam and diffused radiation is referred to as total or global radiation.

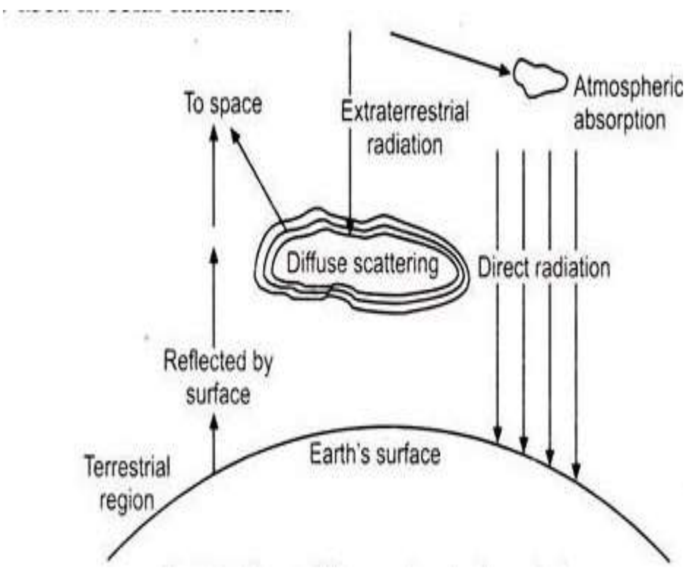

Fig. 1 scattered, diffused, and direct normal solar radiations

So the solar radiation falling on a titled plate is divided into three parts-

1) Beam radiation
2) Diffused radiation
3) Reflected radiation

The summation of these three radiation is the total radiation on a tilted surface

Before calculating the solar radiations one must be aware of solar geometry for a tilted surface (fig.2)

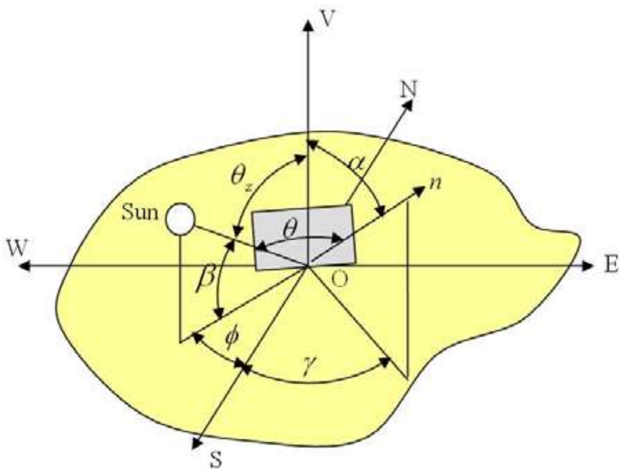

Fig. 2 solar radiation incident on an inclined plane

Here

ϴ= incident angle i.e. angle made by the sun with the normal of the panel

α= tilt angle of the panel

γ= surface azimuthal angle i.e. the angle made by the component of the normal to the panel on the horizontal surface with south

Φ= solar azimuthal angle i.e. angle made by the component of solar radiation in the horizontal surface with south

B= solar altitude angle

θ_z= solar zenith angle

Now

δ= Declination angle i.e. the angle made by the lines joining the centres of the sun and the earth with its projection on the equatorial plane

$$\delta(in\ degrees) = 23.45 \sin[\frac{360}{365} \times (284 + n)] \quad ...(1)$$

L= the latitude of a location is the angle made by the radial line joining the location to the centre of the earth with the projection of the line on the equatorial plane.

ω=the hour angle is an angular measure of time and is equivalent to 15° per hour.

The slope α is the angle made by the plane surface with the horizontal. It can vary from $0°\ to\ 180°$. It can be shown that-

$$\cos\theta = \sin L\,(\sin\delta\cos\alpha + \cos\delta\cos\gamma\cos\omega\sin\alpha) + \cos L\,(\cos\delta\, cos\omega\cos\alpha - \sin\delta\cos\gamma\sin\alpha) + \cos\delta\sin\gamma\sin\omega\, sin\alpha \quad ...(2)$$

Beam radiation

The ratio of beam radiation flux falling on a tilted surface to that falling on horizontal surface is called the tilt factor for beam radiation[1]. It is denoted by r_b.

$$r_b = \frac{I_{bt}}{I_b} \quad ...(3)$$

Here

I_{bt}= beam radiation flux on tilted surface

I_b= beam radiation flux on horizontal surface

It is generally known that southern facing panels, in the northern hemisphere, results in the highest solar irradiation[2]. Therefore γ is kept 0°.

$$\cos\theta = \sin\delta\sin(L-\alpha) + \cos\delta\cos\omega\cos(L-\alpha) \quad ...(4)$$

While for horizontal surface

$$\cos\theta_z = \sin L\sin\delta + \cos L\cos\delta\, cos\omega \quad ...(5)$$

Hence from equation (4) and (5)

$$r_b = \frac{\cos\theta}{\cos\theta_z} \quad \ldots(6)$$

Diffuse radiation

The tilt factor r_d for diffuse radiation is the ratio of diffuse radiation flux falling on the tilted surface to that falling on a horizontal surface. The value of tilt factor depends upon the distribution of diffuse radiation over the sky and on the portion of the sky seen by the tilted surface[1].

$$r_d = \frac{I_{dt}}{I_d} \quad \ldots(7)$$

Here

I_{dt}= diffused radiation flux on tilted surface

I_d= diffused radiation flux on horizontal surface

Since $(1 + \cos\alpha)/2$ is the radiation shape factor for a tilted surface with respect to sky

$$r_d = \frac{1+\cos\alpha}{2} \quad \ldots(8)$$

Reflected radiation

As $(1 - \cos\alpha)/2$ is the radiation shape factor for the surface with respect to the surrounding ground and reflectivity is ρ[1], the tilt factor for reflected radiation is given by,

$$r_r = \rho\left(\frac{1-\cos\alpha}{2}\right) \quad \ldots(9)$$

Also

$$r_r = \frac{I_{rt}}{I_b+I_d} \quad \ldots(10)$$

Here

I_{rt}= reflected radiation flux on a tilted surface

Therefore total radiation flux (I_T) on a tilted surface at any instant is given by [from equation (6), (3) (7), (8), (9) and (10)]

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \quad \ldots(11)$$

III. METHODOLOGY

To determine the fixed optimum solar panel angle that receives maximum annual solar irradiation equation (11) must be found for the whole year in terms of tilt angle and then I_T must be maximized by varying the tilt angle. This process is complex and quite tedious. A simplified approach is to use an Excel spreadsheet to evaluate the total annual irradiation per unit area and the use its solver to maximize the annual solar irradiation. The daily irradiation on the panel at solar time 12pm is calculated at the 21st of each month and it is assumed that the same irradiation is applicable for fifteen days before and after. The procedure for evaluating the daily solar irradiation for 21st of January is herein explained in detail.

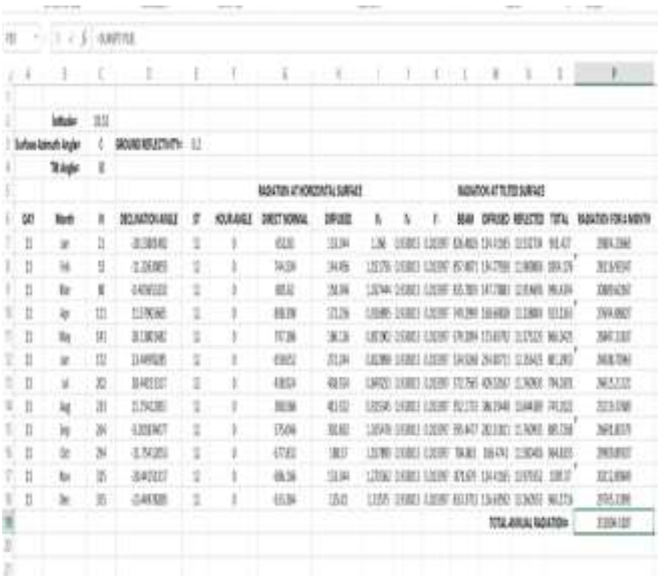

Fig. 3 excel spread sheet showing the cakculation for optimum tilt angle

Figure 3 represents the excel spreadsheet. You can observe that cell C2 contains the latitude of Pune. Cell C3 contains the surface azimuthal angle which is taken as zero as the surface is facing south. Cell E3 has ground reflectivity ρ. Tilt angle is given in cell C4 for the time being it is randomly considered as 30°. Column from cell A6 contains the day of the months that is 21^{st}. Column from cell B6 contains the months. N is the no of the day in a year. For 21^{st} of January it is 21. Column from D6 contains the declination angle calculated by equation (1) the formula in the column cell is $23.45 * \mathrm{SIN}((2 * \mathrm{PI}()/365) * (284 + \mathrm{C7}))$.

Solar time is taken as 12pm for which hour angle is zero. The values of direct normal and diffused radiation for a horizontal surface are obtained from radiation book. Refer fig. 4 and fig. 5.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Jan	5.556	8.334	58.338	97.23	122.232	127.788	133.344	133.344	127.788	113.898	88.896	52.782	5.556	0
Feb	0	19.446	75.006	111.12	130.566	138.9	144.456	138.9	133.344	116.676	102.786	72.228	19.446	0
Mar	2.778	36.114	91.674	127.788	141.678	152.79	158.346	155.568	152.79	147.234	130.566	97.23	36.114	2.778
Apr	5.556	52.782	111.12	138.9	155.568	166.68	172.236	175.014	175.014	172.236	161.124	122.232	58.338	5.556
May	5.556	75.006	127.788	152.79	166.68	180.57	186.126	191.682	191.682	183.348	166.68	133.344	77.784	8.334
Jun	11.112	86.118	147.234	188.904	219.462	255.576	272.244	266.688	261.132	241.686	211.128	152.79	94.452	13.89
Jul	5.556	80.562	169.458	250.02	358.362	405.588	438.924	425.034	297.246	330.582	247.242	172.236	88.896	8.334
Aug	5.556	55.56	130.566	233.352	363.918	338.916	413.922	452.814	333.36	397.254	302.802	202.794	88.896	5.556
Sep	2.778	44.448	116.676	180.57	252.798	294.468	302.802	316.692	288.912	255.576	208.026	138.9	41.67	2.778
Oct	0	22.224	100.008	144.456	155.568	163.902	180.57	188.904	191.682	180.57	144.456	94.452	19.446	0
Nov	0	11.112	63.894	97.23	113.898	125.01	133.344	133.344	127.788	113.898	97.23	55.56	8.334	0
Dec	0	5.556	52.782	88.896	113.898	122.232	125.01	122.232	116.676	100.008	80.562	50.004	5.556	0
Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 4 Diffused radiation for a horizontal surface

	DNI													
	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Jan	-5.556	2.778	88.896	255.576	486.59	583.38	652.83	655.608	580.602	455.592	277.8	102.786	8.334	0
Feb	0	16.668	147.234	344.472	533.376	677.832	744.504	752.838	683.388	552.822	352.806	152.79	13.89	0
Mar	-2.776	33.336	197.238	397.254	591.714	733.392	805.62	833.454	730.624	575.046	375.03	177.792	25.002	-2.778
Apr	-2.776	44.448	211.128	425.034	608.382	736.17	808.398	800.064	722.28	572.268	377.808	186.126	44.448	0
May	0	55.56	230.574	441.702	619.494	733.392	791.286	783.396	705.612	566.712	388.92	205.572	52.782	0
Jun	0	52.782	213.906	377.808	541.71	602.826	658.052	647.274	511.268	477.835	313.914	188.904	44.448	0
Jul	0	27.78	158.346	302.802	363.918	400.032	458.924	475.038	481.786	375.03	297.246	175.014	38.892	2.778
Aug	0	27.78	166.68	236.13	286.134	347.25	380.586	372.244	341.578	275.022	213.906	125.01	11.112	0
Sep	0	27.78	180.57	338.916	436.146	494.484	575.046	552.822	475.038	433.932	280.578	147.234	27.78	-2.778
Oct	0	8.334	111.12	297.246	491.706	630.606	677.832	663.942	575.046	486.59	363.91	180.008	11.112	0
Nov	0	5.556	105.564	286.134	475.038	616.716	666.156	688.944	611.16	480.594	280.578	105.564	5.556	0
Dec	0	2.778	80.562	244.464	411.144	558.378	633.384	647.274	577.824	452.814	280.578	91.674	2.778	0
Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 5 Direct normal radiation for a horizontal surface

Now r_b is calculated equation (6),The formula in cell I7 is In the next column r_d is calculated by $(\mathrm{SIN}(D7 * (\mathrm{PI}()/180)) * \mathrm{SIN}(\$C\$2 * (\mathrm{PI}()/180) - \$C\$4 * (\mathrm{PI}()/180)) + \mathrm{COS}(D7 * (\mathrm{PI}()/180)) * \mathrm{COS}(F7 * (\mathrm{PI}()/180)) * \mathrm{COS}(\$C\$2 * (\mathrm{PI}()/180) - \$C\$4 * (\mathrm{PI}()/180)))/(\mathrm{SIN}(\$C\$2 * (\mathrm{PI}()/180)) * \mathrm{SIN}(D7 * (\mathrm{PI}()/180)) + \mathrm{COS}(\$C\$2 * (\mathrm{PI}()/180)) * \mathrm{COS}(D7 * (\mathrm{PI}()/180)) * \mathrm{COS}(F7 * (\mathrm{PI}()/180)))$.equation (8) and the formula in cell J7 is $0.5 * (1 + \mathrm{COS}(\$C\$4 * (\mathrm{PI}()/180)))$. r_r in the next column is calculated by the equation (9), formula for that cell K7 is $0.5 * (1 - \mathrm{COS}(\$C\$4 * (\mathrm{PI}()/180))) * \$E\$3$.

Now the beam radiation at tilted surface is calculated in column L by the equation (3), formula for it in the cell L7 is $\mathrm{I7} * \mathrm{G7}$. Then the diffused radiation at tilted surface is calculated in column M by the equation (7), the formula in cell M7 is $\mathrm{H7} * \mathrm{J7}$.And the last reflected radiation at tilted surface is calculated in column N by the equation (10), the formula in cell M7 is$(\mathrm{G7} + \mathrm{H7}) * \mathrm{K7}$. In the next column all this radiations are added to find the final radiation on a tilted surface. In the next column the total radiation is multiplied by no of days in that month. Same process is carried out for all other months and then monthly radiations are added to get the annual radiation in cell P19.

After finding the annual radiation excel solver is used to maximize the value of annual radiation (P19) while varying the tilt angle (C4). So for $\gamma = 0° \ and \ \rho = 0.2$ the optimum tilt angle obtained is 20.1393°.

IV. CONCLUSION

In this paper a simple model based on spreadsheets is used to predict the optimum solar collector tilt angle.

The model utilizes reflectivity and given radiation for a horizontal surface to obtain the optimum tilt angle. It is observed that from zero as tilt angle increases the annual radiation increases and reaches a maximum value (similar to bell curve). After that if the tilt angle is further increased the annual radiation goes on reducing. Also for the optimum tilt angle, the monthly solar irradiation during winter months are increased. Conversely, the solar irradiations for summer months are decreased.

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