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Optimal Conversion of Solar Energy of Statically Mounted Systems in India

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Abstract: In this paper, the optimum energy conversion conditions of stationary panels are calculated at different latitudes for 180 days of a year to cover various angular orientation of sun's rays on the earth. On a given day, the incident energy flux of the sun is resolved into three components, and the conversion efficiency is based on the flux normal to the panels. The efficiency of conversion is measured with respect to a solar tracking process. The number of days in a given year are divided into two groups – one between the winter solstice and the spring equinox, and another between the spring equinox and the summer solstice.

The results show that, there exist two maxima, one for each of the two periods. By setting the panels at each of these maxima significant (of the order of 5% over the single optimal setting condition also derived in this work) improvement in energy conversion can be achieved.

Key words: Alternative energy, efficiency, solar energy conversion, photovoltaic systems, India.

Introduction

India is a country which extends over vast areas in terms of latitude starting from the Andaman islands (6ºN at its south most point) to Leh in Laddakh (34.17ºN). The climate at these places is quite diverse due to their location near the sea to that on the mountain. At Leh, the solar energy primarily exists in the form of beam radiation because there is very little scattering due to the lack of dust. Moreover, there is a shortage of vegetation in Laddakh, which leads to the scarcity of wood to be used as a fuel. Tibet is one of the places in the world where they have found greater use of solar energy for cooking. Due to the remoteness of the place also, converting the solar energy into electricity is another attraction.

Today, global warming is melting the polar ice caps and causing stronger winds which take the form of hurricanes or typhoons. This results in great damage to property and also results in loss of lives. No country has remained untouched by these effects.

To make matters worse, experts predict that we will soon see shortage in oil supplies due to the increased demand for oil in both, the industrialized and newly industrializing countries. (Bentley, 2004). The global price of the crude oil has already reached quite high which is beyond the affordability for many in poorer countries. It is a sad fact that various governments in the world have not taken measures to provide alternatives to the poor.

Solar energy provides us with an alternative where there is no pollution of the environment and it enhances in a way – the energy reserves if proper method is found to harness this form of energy.

The main uses of the solar energy have been in converting it into (a) heat, for example. Directly heating homes or water heating, where the sun's rays are incident on a panel containing circulating water in tubes and (b) electricity using photovoltaic panels.

In majority of cases, these panels are held stationary at an angle from the horizontal and they face due south.

Nomenclature

$[R\ (Y1, \eta)]$	Rotation matrix to transform incident solar energy vector
$\{\mathbf{I}\}^1$	The intensity vector in X1 – Y1 – Z1 co-ordinate frame
$\{\mathbf{I}\}^2$	The intensity vector in X2 – Y2 – Z2 co-ordinate frame
α	Angle in vertical plane
α_s	Angle in horizontal plane
Y	Latitude of the place
δ	Declination
h_s	Hour angle at any instant of time
h_{sr}	Hour angle at sunrise measured from noon
I_0	Incident solar energy intensity of beam radiation
N	Day number of a year
R	Distance from the earth to sun

This angle is not changed irrespective of seasons. The selection of this angle is quite arbitrary and this arbitrary selection does not help in converting this energy in an optimal manner. This paper will show that one can very easily achieve this objective.

There have been different approaches to achieve the objective mentioned above (proper method of harnessing solar energy). In one approach (Luque et al., 1980; Luque et al., 1984; Forrest and Xue, 2005; Vorobiev et al., 2004) efforts have been made to enhance the energy conversion at the solar cell level. This leads to increased yield in the energy from say 12% to 15% or so of the incident energy – as far as the conversion of sun's energy into electricity is concerned.

The second approach uses improved control in power generation (Hiyama et al., 1995; Husain et al., 1995; Huynh and Cho, 1999; Huynh and Cho, 1996; Baz et al., 1984; Farber et al., 1976; Hiyama et al., 1994; Maish, 1990; Ro and Rahman, 1998; Siri et al., 1993). In this approach, the electrical parameters involved in the power generation are altered through the control process which include the use of microprocessors in some cases. One can also refer to some other relevant references (Mellit et al., 2005; Bird and Riordan, 1986; Iskender, 2005; Klutcher, 1979; Satyamurty and Lahiri, 1992; Sen, 1998; Vorobiev et al., 2004).

In a tracking process, the solar panels are mounted on a mechanism which is driven by a motor. The two necessary angles are adjusted in such a way that the sun's rays are always normal to the panels.

While the tracking process yields the maximum possible energy conversion yet, the majority of the energy conversion units are not designed based on tracking. In such cases, the receiving surface is held at a constant angle from the horizontal irrespective of the season.

In India, harnessing the solar energy by tracking is an exception to the rule. Most frequently, they are used in a static manner for heating water in hotels, schools or college hostels or in some cases at homes and hospitals.

The objective of this work is to show that such an arrangement of an arbitrary angle is not appropriate and that the determination here is made of optimum angles in each of the two periods which are between – (a) the winter solstice and spring equinox, and (b) spring equinox and summer solstice.

Theoretical Considerations

Figure 1 shows the sun's rays are incident on a horizontal plane and its direction is defined with the help of two angles – α_s and α which are in the horizontal and vertical planes respectively. Suppose, the distance AC is equal to R then the components in the X1 and Y1 directions will be (refer to Figure 2 for X1 and Y1 directions).

$$X_B = R \cos(\alpha_s)$$

One can express the above equation in a non-dimensional manner by writing

$$(X_B/R) = \cos(\alpha_s) \tag{1}$$

Similarly, one can write

$$(Y_B/R) = \sin(\alpha_s) \tag{2}$$

If the intensity of solar energy is I_0 then the three components in X1, Y1 and Z1 co-ordinates will be

$$I_{X1} = -I_0 \cos(\alpha) \cos(\alpha_s) \tag{3}$$

$$I_{Y1} = -I_0 \cos(\alpha) \sin(\alpha_s) \tag{4}$$

$$I_{Z1} = -I_0 \sin(\alpha) \tag{5}$$

Let us represent the solar energy by a vector $\{\mathbf{I}\}^1 = \{I_{X1}, I_{Y1}, I_{Z1}\}^T$. In Figure 2, one can express the vector $\{\mathbf{I}\}^2$ in terms of $\{\mathbf{I}\}^1$ in the matrix form as (Craig, 2005).

$$\underset{3 \times 1}{\{\mathbf{I}\}^2} = \underset{3 \times 3}{[R\ (Y1, \eta)]}\ \underset{3 \times 1}{\{\mathbf{I}\}^1} \tag{6}$$

In Figure 2, the X2 direction is perpendicular to the panel, and the angle

$$(X2 - O - X1) = \eta = (90 - Y) \tag{7}$$

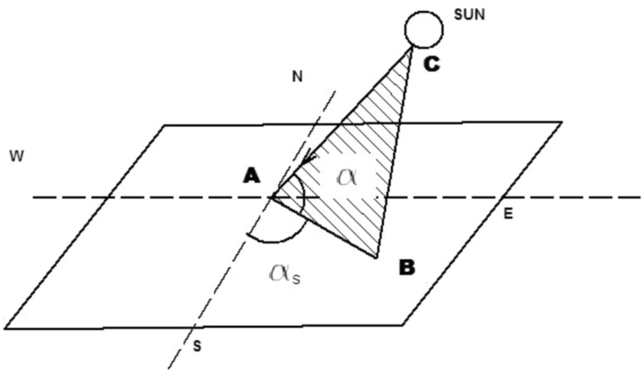

Figure 1: Diagram showing the solar ray direction using two angles.

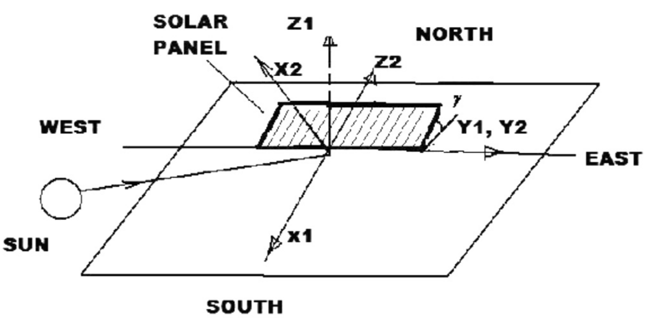

Figure 2: Solar panel facing south and tilted (see equation 6).

where, Y is the angle from the horizontal plane as shown in Figure 2. In Eq. (6), $[R\,(\mathrm{Y1}, \eta)]$ is the rotation matrix to transform the vector $\{\mathbf{I}\}^1$ from X1- Y1 -Z1 space to X2- Y2 - Z2 space about the Y1 axis. A (3 × 3) transformation about Y axis by an angle θ is given by

$$[T_y] = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad (8)$$

In Eq. (6), one needs to use θ in place of η as well as the three rows and columns to transform a 3 × 1 incident energy vector $\{\mathbf{I}_0\}$.

It should be remembered that we are only interested in the negative component in the X2 direction, i.e., I_{X2} should be negative. If this vector component is positive then there is no solar energy conversion because, in that case, the sun would shine from behind the panels.

One can calculate α_s and α using the following formulas (Kreider and Kreit, 1979; Kreith and Black, 1980; Duffie and Beckman, 1991).

$$\delta = 23.45 \sin \{(360/365)\,(284 + N)\} \quad (9)$$

where δ is the declination of the sun in degrees, and N is the day number, which is the number of the day in a year. For example, on January 1, N is equal to 1.

The time of sunrise, h_{sr} in hour angle from the noon is calculated from

$$h_{sr} = \cos^{-1} \{-\tan(\delta) \tan(\mathrm{Y})\} \quad (10)$$

Denoting the instant of time in terms of the hour angle from the noon as h_s, one can write

$$\sin(\alpha) = \cos(\mathrm{Y}) \cos(\delta) \cos(h_s) + \sin(\mathrm{Y}) \sin(\delta) \quad (11)$$

and by expressing the angles in degrees.

$$\alpha_s = \sin^{-1} \{\cos(\delta) \sin(h_s)/\cos(\delta)\}$$
$$\text{if } \cos(h_s) > \{\tan(\delta)/\tan(\mathrm{Y})\} \quad (12)$$

or $$\alpha_s = 180° - \sin^{-1} \{\cos(\delta) \sin(h_s)/\cos(\alpha)\}$$
$$\text{if } \cos(h_s) < \{\tan(\delta)/\tan(\mathrm{Y})\} \quad (13)$$

Results and Discussions

Setting of the Panel Angle Once for All

To study the effect of latitude on the conversion efficiencies of the stationary mounted solar panels, four different places in India at different latitudes were selected and their latitudes are shown in Table 1. These places cover all of India.

Figures 3 to 8 show the sun's trajectory on the horizontal plane at various locations in winter (N = 1), and summer (N = 182). Figures 3 and 4 show the position

Table 1: Efficiencies at four different places in India

Name of the place	*Single Setting*			*Two Settings*				
	Latitude (north) (degrees)	*Angle Y (degrees)*	*Average efficiency*	*Angle (Summer) Y1 (degrees)*	*Efficiency 1 (Summer)*	*Angle (winter) Y2 (degrees)*	*Efficiency2 (winter)*	*Average Efficiency (Y1 and Y2)*
Andamans	6.0	4	0.609	-16	0.65	26	0.67	0.660
Bangalore	12.58	12	0.61	-8	0.638	34	0.682	0.660
Patna	25.62	24	0.611	3	0.614	45	0.705	0.660
Leh	34.17	33	0.613	12	0.595	53	0.724	0.660

of the sun in the morning hours at Andaman for $N = 1$ (winter), and $N = 182$ (summer) when the days are slightly short and long respectively. This is because Andaman Islands are situated near the equator. It (this difference) is much more pronounced between Figures 7 and 8 at Leh. These figures were obtained by starting with Eq. (8) and performing the calculations corresponding to Eqs. (9) to (12) followed by Eqs. (1) and (2), i.e., they are the plots of (Y_B/R) versus (X_B/R) – non-dimensional distances.

The morning sunshine period (between the sunrise to noon) was divided into 100 intervals, and calculations were made for each of the intervals. By symmetry about the noon, the afternoon values would be the same as the morning values.

For $N = 1$ in Figure 3, the sun remains on the south side (refer to Figure 2) of the vertical plane containing the Y1 and Z1 axes. This being the winter in the northern hemisphere, the days are shorter as compared to those in summer. The curvilinear length in Figure 7 is much shorter than that of Figure 8. One can state this in another way where one can say that the spans of angles α_s and α are much greater in Figure 8 as compared to Figure 7 – as far as each of these two angles are concerned.

These larger spans of the angles in summer result in reduced conversion efficiency of these panels which are held at a fixed angle facing south in the northern hemisphere. The greater the span the greater will be the obliquity of the incident rays from the normal to the panel. This increased span results from the increase in latitude of a place. The difference in span between the summer and the winter is reduced near the equator – for example in the case of Andaman.

One also has to recognize the fact that the sun shines for longer hours during the summer. So, the reduction in efficiency in summer months causes worse capital utilization. This is unavoidable unless we go for tracking when the efficiency would be 100% but that requires dealing with the complexity in mechanism design and that is not the objective of this work. The objective here is to improve upon the efficiencies of the presently used static solar systems or those new ones which are going

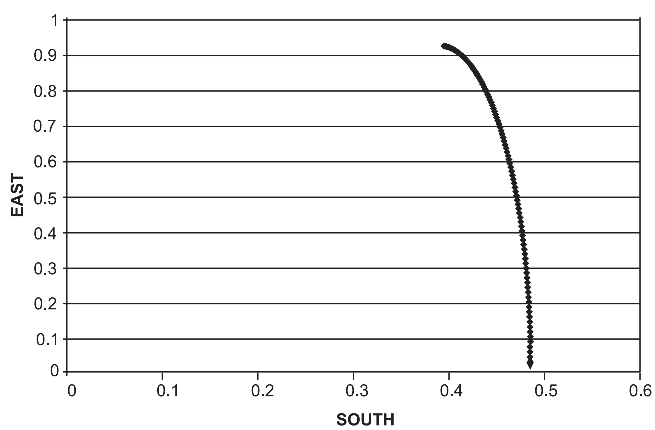

Figure 3: Solar trajectory at Andaman islands, $N = 1$.

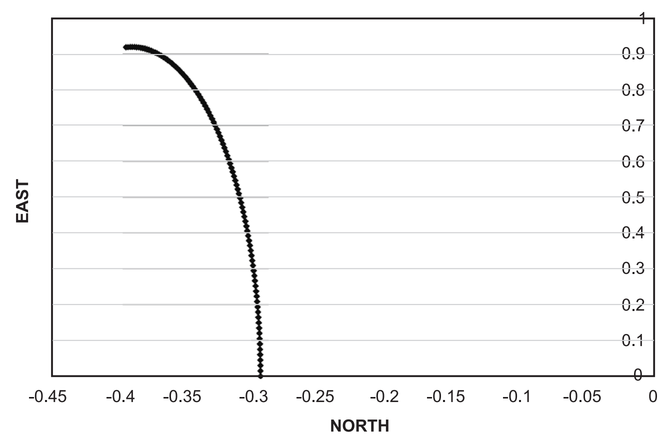

Figure 4: Solar trajectory at Andamans, $N = 182$.

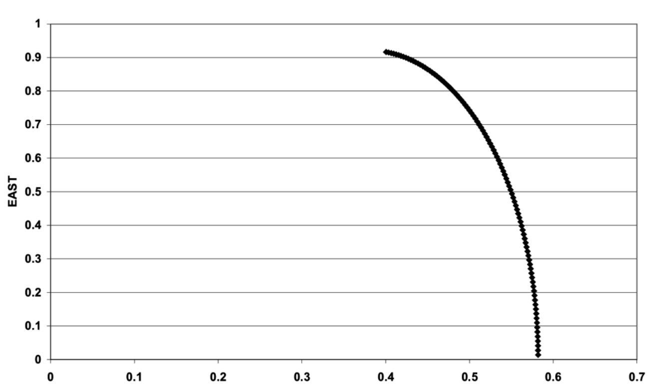

Figure 5: Solar trajectory at Bangalore, $N = 1$.

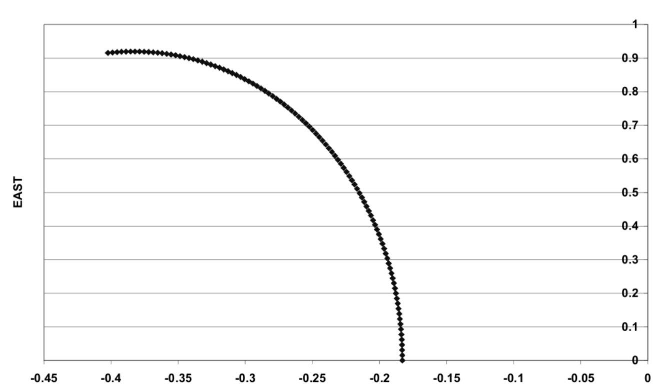

Figure 6: Solar trajectory at Bangalore, $N = 182$.

to be built. For the presently used ones, they can very easily be modified using the results of this work.

The fact that the sunrise takes place in the south in the winter, and in the north in the summer, clearly points out the fact that the efficiency of the panels would not be very good because they face south all the year round.

Figures 5 to 8 show the solar trajectories at Bangalore and Leh. For Patna, it is not shown here but the trajectories there follow the same trend. At Leh in Figure 8, the sun rises in the north–east but crosses the east-west line to come to due south at noon which is different from that of Bangalore where it stays in the north only (Figure 6); but the panels at Bangalore face south. Whatever energy the panels receive at Bangalore in such a situation is because of the vertical angle, α, when it gets to sufficiently high values.

In order to overcome this problem, it was decided to find the optimum angle for 180 days which is approximately six months of a year – which is approximately a complete period. The angles will repeat after this period. Therefore, the calculations were performed for angles between – 85 to 85 degrees at one degree interval for all the four places mentioned earlier. Figure 13 shows the panels at positive and negative values of their orientation from the horizontal plane.

Figure 9 shows the average conversion efficiency as a function of angle at which the panel is held from the horizontal plane represented by Y in Figure 2. This graph has three different plots (180 days, summer, and winter). The discussion in this paragraph is about the 180 days only. For the other two, it will be done in the next section. The number of days considered here are 180 from the winter solstice. This efficiency reaches a peak value of 0.61 at 12 degrees. If the panel is held at 12 degrees and then the variation of the efficiency with the days is shown in Figure 14. In this figure (Figure 14), one can see that the efficiency increases first with the increase in the number of days from the winter solstice; it reaches a peak value of 0.64 on the 79th day and then it decreases. One can obtain results similar to Figure 14 for other places also.

One needs to note that considering $I_0 = 1$, the conversion efficiencies of these stationary solar panels are plotted based on $\{\mathbf{I}\}_2$ given in Eq. (6). We have to

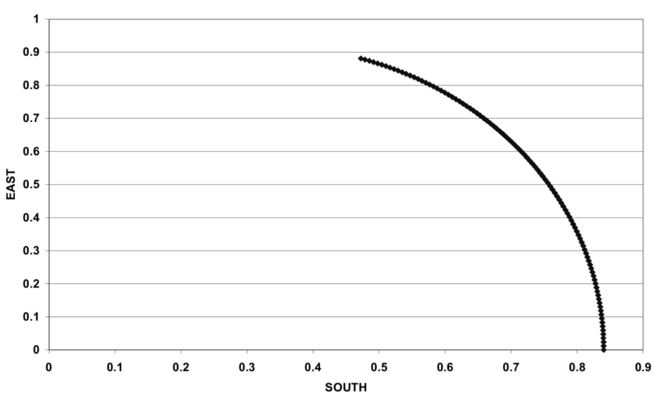

Figure 7: Solar trajectory at Leh, $N = 1$.

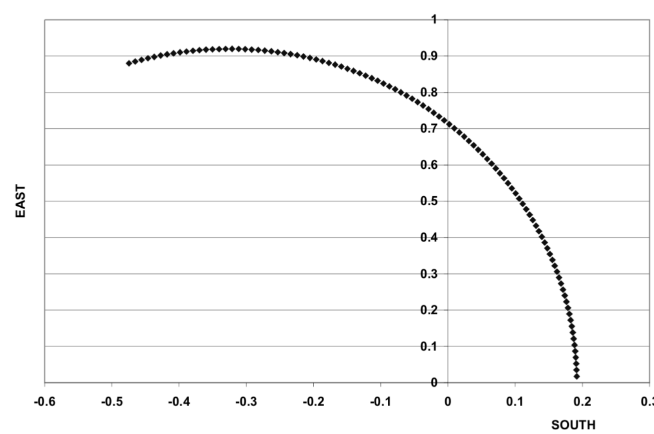

Figure 8: Solar trajectory at Leh, $N = 182$.

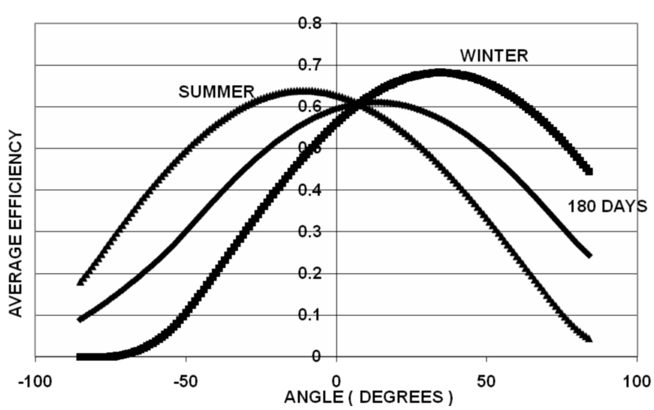

Figure 9: Efficiency variations at Bangalore.

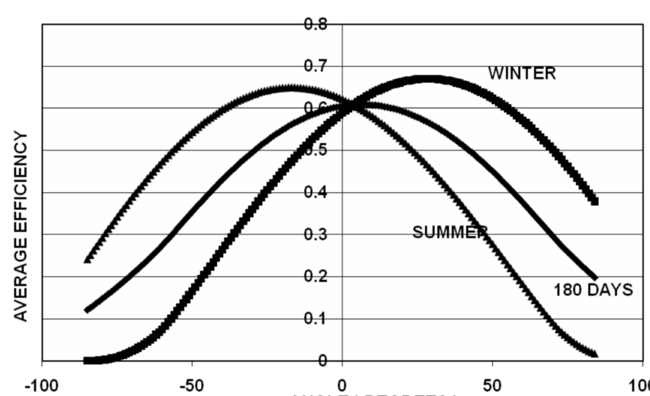

Figure 10: Efficiency variations at Andamans.

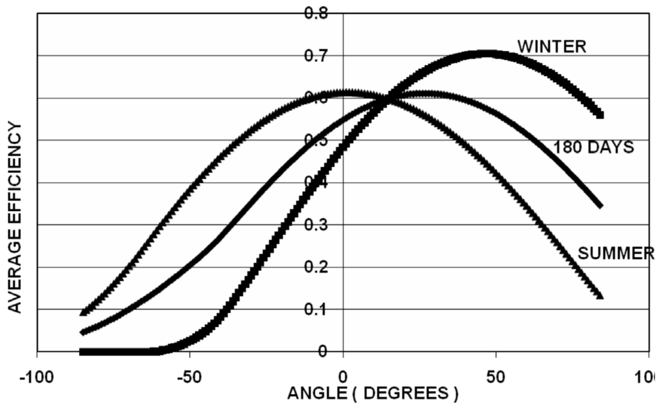

Figure 11: Efficiency variations at Patna.

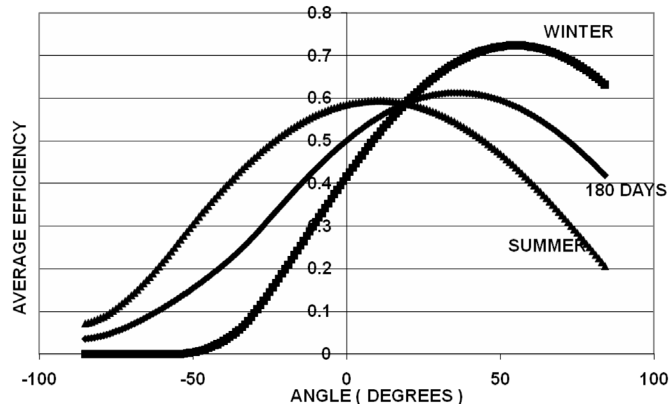

Figure 12: Efficiency variations at Leh.

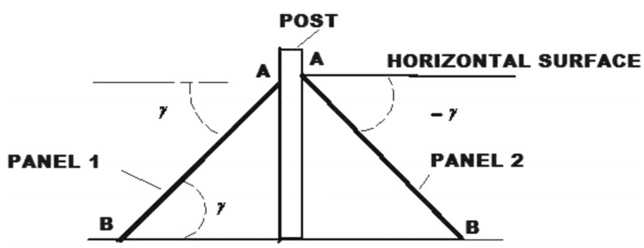

Figure 13: Inclination of panels from horizontal surface (panel 2 at negative angle).

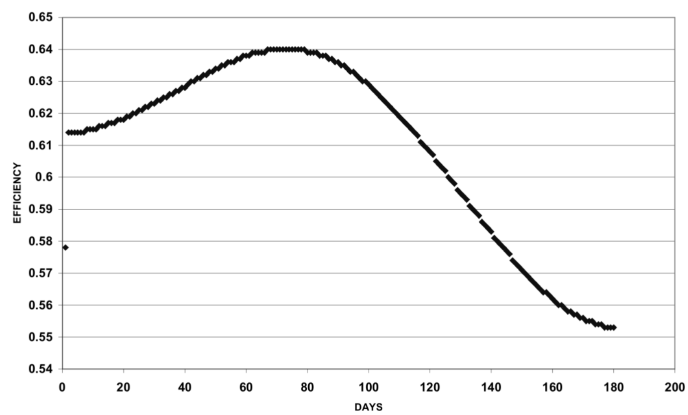

Figure 14: Efficiency variations with days at Bangalore.

remember that the energy conversion takes place only when $\{\mathbf{I}_{X2}\}^2$ is negative. The components $\{\mathbf{I}_{Y2}\}^2$ and $\{\mathbf{I}_{z2}\}^2$ do not contribute to the energy conversion.

One possible way to further increase the efficiency can be by setting off angle of the panel twice (fine tuning of the angle) – each of 90-day span; once between the winter solstice and the spring equinox, and the other between the spring equinox and the summer solstice.

Setting of the Panel Angle Twice a Year

Figure 9 shows the variation of average efficiencies (summer and winter) with angle. It shows two optimums for each of these (summer and winter) curves. The winter setting is for 90 days after the winter solstice, and then it is summer for the balance of 180 days. The value of the peak efficiency for the summer is less than that of the winter, and the angle at which this peak occurs also is less than that of the winter. Due to the low altitude angle of the sun in the winter, the angle Y in Figure 2 has to be higher to have sunrays incident on it from the normal direction. The results are summarized in Table 1 for each of the places. The plots of other places are given in Figures 10 to 12.

Looking at the Table 1, one can see that the efficiency is slightly increased by two settings as compared to one setting. On the other hand, if we go for a tracking process then this efficiency becomes equal to 1 and this will be a considerable increase.

Conclusion

In this work the mathematical equations for the normal incidence on the solar panels were derived first. Then, based on the studies for 180 days from the winter solstice for cities of the world at varying latitudes, the following conclusions can be drawn:

1. There exists an optimum angle for the panels at various latitudes which yields an efficiency of 0.61 approximately.
2. If the angle is set twice in a year then this efficiency can be increased to 0.66.
3. The efficiency between the spring equinox to the summer solstice (second period) is less than that between the winter solstice and the spring equinox (first period).

4. The decrease in the efficiency in the second period is because of the increased span of the horizontal and vertical angles of sun's incident rays.

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About the Author

Prof. V. Subramanian, after completing his PhD from U.S.A with a Fulbright Fellowship and teaching briefly at McGill University, Canada, joined Jawaharlal Nehru University in 1975. Since then he has been working on global rivers for over three decades; incidentally, all the students hostels in JNU are named after rivers of South Asia. More than 35 students did their PhD under him over the years and he has authored or co-authored more than 175 technical international publications as well as books. He set up academic activities on rivers in South Asia at JNU way back in 1975 and has since been associated with several international institutions/organizations either as member or guest faculty from time to time. At present he is working as Emeritus Fellow in Environmental Sciences at JNU.

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