Tilt angle optimization for maximization of solar irradiance for a Photo-Voltaic panel for Chandil, Jharkhand

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ABSTRACT

Being positioned over subtropical belt, India has ample amount of sunlight throughout the year. Thus, energy from day light is one of the most promising sources to fill the demand-supply gap of power and this can be done effortlessly by PV technology. In this work we have tried to explore the possibilities to achieve maximum benefit of day light energy by adjusting the PV system in accordance with the sun's position. This can be done by placing the panel over inclined axis as compared to horizontal. The most effective inclination has been computed for Chandil, located in the state of Jharkhand, on monthly basis throughout the year. The orientation was changed from 0°-90° with lap of 0.05° in order to compute maximum radiation. It has been concluded that the average annual tilt in the axis of panel should be 22.454° which increases the energy by utmost 13%.

Keywords: Tilt angle, Matlab/ Simulink, Solar geometry, Renewable energy.

INTRODUCTION

Indian subcontinent is one of the major evolving economies on the globe. Amidst of rigorous infrastructural developments, prompt communication advancements, rapid industrial expansions, swift livelihood upliftment, lies the extinction of natural resources. Power: one of the core foundation pillars of a nation's growth has been chiefly reliant on natural fossils in case of India. On one side the nation has declared 100% electrification few years ago and on the other hand coal imports has increased tremendously to about 92 metric tons during April-August 2021 (Business Standard, August 2020). Though we have travelled a long way from mere 1306 MW in 1947 to a giant of 389 GW of installed power generation capacity (Ministry of Power, India), the dependence on conventional sources has augmented too. This is the reason; we are continuously concentrating on novel alternative methods of power generation. The Figure 1 below shows the share of power generation among various sources in India (Central Electricity Authority).

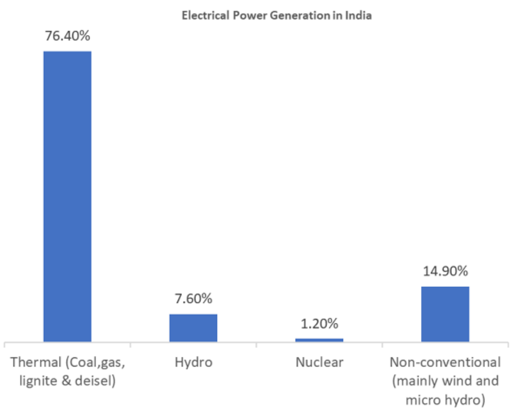

Figure 1. Electrical Power Generation share in India

Radiations from the sun can either be directly converted to electricity by means of PV technology or can be utilized indirectly by accessing the heat produced due to radiation through a solar concentrator. However, the PV technology is most common and economic. It can also be used on smaller scales in islanded and off grid modes. India is geographically situated on the subtropical belt hence is gifted with ample amount of sunlight throughout the year. The following Figure 2. represents the variation of solar irradiance of some of the cities throughout the year (Nallapaneni Manoj Kumar et. Al., 2017).

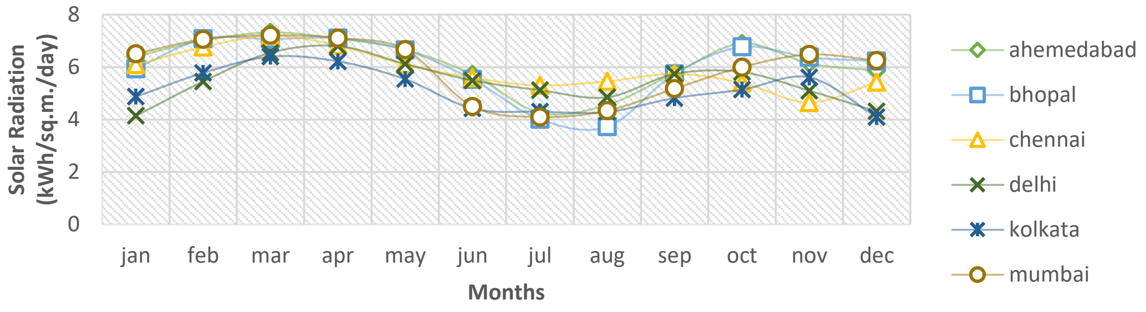

Figure 2. Solar radiation pattern of various cities of India throughout the year

Precise angle of inclination was computed for university campus in Pakistan for unit KW system (Q.A.Menon, 2021). Implementation of software computation techniques has been done and most appropriate slant has been calculated by utilizing the Particle Swarm Optimization method (T.V. Dixit et al, 2017). Novel computational expression for the calculation of slant of the panel is suggested in the Himalayan region (A. Sharma et al, 2021). Hypothetical mathematical expressions can also be utilized for the computation of slant angles and this has been done by applying the Kepler's motion theoretical model (Liu, Tong, 2021). Separate result angles were obtained for yearly fixed panels and monthly fixed panels. (Getu Hailu et al, 2019) Slant angle optimization and alignment of PV- Heater systems have been done in Canada considering isotropic and anisotropic equations. The latter gave better and sustainable results and proper alignment direction of panel was suggested to be E-W. Senegal, Africa is divided into various microclimate zones and analysis for angle of inclination of panels has been observed on daily, monthly and yearly basis. The results depict that angle equivalent to geographic latitude is not the precise one (Sarr, A., 2021). Western and central African terrains have been analyzed for general endorsements regarding effects alignment estimation of PV systems (Kokouvi Edem N'Tsoukpoe, 2022). Various PV techniques including monocrystalline, thin film and poly crystalline are considered for estimation of orientation alignment in Burder (Ramazan Ayaz, 2017). The tilt angle range differs for all the techniques on monthly and annular base. MVPA along with PSO was applied in Yambu for the estimation of annular tilts (Ramli MAM, Bouchekara HREH, 2021). Different reflector technologies used in India have been analyzed for optimization of slants and their effects experimentally as well as mathematically (Yathin Krishna, 2020).

STUDY LOCATION

The location for detection of optimum angle of inclination for PV panels in this research is Chandil. In the midst of dense forest, hills and valley is the grand Chandil reservoir over Swarnarekha river which has hydroelectric generation plant of 8MW capacity. This block has a total of 103 villages with wide population range of 12- 4300 inhabitants. The total area of the block is about 375.67 km^2 which includes 367.82km^2 of rural area and 78.5 km^2 of urban land. The geographical coordinates of Chandil town are 22.9615° N, 86.0657° E and elevation above mean sea level is 246 m.

SOLAR CALCULUS

To compute the total solar flux falling on an inclined photovoltaic panel, it is essential to calculate the amount of radiation falling directly (beam radiation), diffused radiation and reflected radiation. This can be numerically denoted as (C. A. Tirmikci et. Al., 2018):

$$TSR = MBR * RB + MDR * RD + H0 * \rho * \frac{(1-cos\sigma)}{2} \quad (1)$$

In the above equation (1): TSR is the total solar radiation in KWh/sq.m./day, MBR is mean beam radiation in KWh/sq.m./day, MDR mean diffused radiation in KWh/sq.m./day, RB is the inclination coefficient of beam solar radiation, RD is the inclination coefficient of diffused solar radiation. H0 is the monthly average daily extra-terrestrial radiation in KWh/sq.m./day, ρ is the reflectivity of ground (this is a constant value of 0.2 in case of ploughing ground and 0.7 for snow cover) (Patrapalli Durga Venkata Lakshmi et.al., 2018), σ is the angle of inclination of the photovoltaic panel in degrees.

RD (inclination coefficient for diffused radiation) can be empirically deduced using the following relationship (Duffie et. Al., 2006).

$$RD = \frac{MBR}{H0} * RB + \left(1 - \frac{MBR}{H0}\right) * \left(1 + \frac{cos\sigma}{2}\right) * \left[1 + \sqrt{\frac{MBR}{H0}} * sin\left(\frac{\sigma}{2}\right)^3\right] \quad (2)$$

H0 (monthly average daily extra-terrestrial radiation in KWh/sq.m./day) can be calculated with the help of following empirical relationship

$$H0 = \frac{24}{\pi} * SC(1 + 0.33 * cos\frac{360d}{365})(cos\varphi * cos\tau * sin\alpha + \alpha\frac{\pi}{180} * sin\varphi * sin\tau) \quad (3)$$

In the above equation (3), SC denotes the solar constant whose numerical value is taken as 1.367 KW/sq.m. (K. Bakirci, 2012). Φ represents the geographical latitude of the location, τ is the angle of declination and α depicts the sunset hour angle. The angle of declination τ and the sunset hour angle can be computed using the following equations

$$\tau = 23.45\ sin\left[\frac{360\ (D+284)}{365}\right] \quad (4)$$

$$\alpha = cos^{-1}(-tan\varphi * tan\tau) \quad (5)$$

RB (inclination coefficient of beam solar radiation) can be computed with the help of following equation (6)

$$RB = \frac{(\cos(\varphi-\sigma) * \cos\tau * sin\upsilon) + (\upsilon * \sin(\varphi-\sigma) * sin\tau)}{(cos\varphi * cos\tau * sin\alpha) + (\alpha * sin\varphi * sin\tau)} \quad (6)$$

Here, υ is the sunrise hour angle which can be calculated by the following equation (7)

$$\upsilon = \min[cos^{-1}(-tan\varphi * tan\tau), cos^{-1}(-\tan(\varphi - \sigma) * tan\varphi) \quad (7)$$

Liu and Jordan relationship has been utilized for computation of MDR mean diffused radiation in KWh/sq.m./day (B.Y.H. Liu et. Al., 1960). According to this relationship, the value of MDR depends upon the clearness index KT which is the ratio of HG and H0.

$$KT = \frac{HG}{HO} \quad (8)$$

HG is the monthly average daily global horizontal irradiance in KWh/sq.m./day.

$$MDR = HG * \{(1.390 - 4.027 * KT) + (5.531 * KT^2) - (3.108 * KT^3)\} \quad (9)$$

HG can be calculated using the following calculation (Sudhakar, K. and T. Srivastava, 2013)

$$HG = H0 * (A1 + B1 * \left(\frac{S}{SMAX}\right)) \quad (10)$$

Here, S is the monthly mean of sunshine hours per day, A1 and B1 are constants whose values can be computed using the equations (11) and (12) and SMAX is the monthly mean of maximum possible hours of sunshine per day. Mathematical equation to calculate SMAX is given in equation (13). EL represents the elevation of geographic location above mean sea level expressed in kilometers. (K.N. Shukla, 2015, Lof, G.O.G., J.A. Diffie and C.O. Smith, 1996, Modi, V. and S.P. Sukhatme, 1979)

$$A1 = -0.309 + (0.539 * cos\varphi) - (0.0693 * EL) + (0.290 * \left(\frac{S}{SMAX}\right)) \quad (11)$$

$$B1 = 1.527 - (1.027 * cos\varphi) + (0.0296 * EL) - (0.359 * \left(\frac{S}{SMAX}\right)) \quad (12)$$

$$SMAX = (2 * \alpha)/15 \quad (13)$$

Finally, MBR can also be computed mathematically using the following equation,

$$MBR = HG - MDR \quad (14)$$

WORK FLOW

Following Figure 3 depicts the flowchart for computation of maximum irradiance obtained by optimizing the angle of tilt of PV panel. In case of Chandil various static parameters are: Latitude φ =22.97°; Elevation EL= 0.246 kms; Solar constant SC= 1.367 KW/sq.m.; Ground reflectivity ρ=0.2. By utilizing the equations 1-14, applying various constants and following the flow chart, one can easily calculate the irradiance level at different inclinations and hence the most effective inclination can be deduced for maximization of solar irradiance on the PV plane. The annual angle of declination τ has been shown in the Figure 4 considering 21st of every month as average.

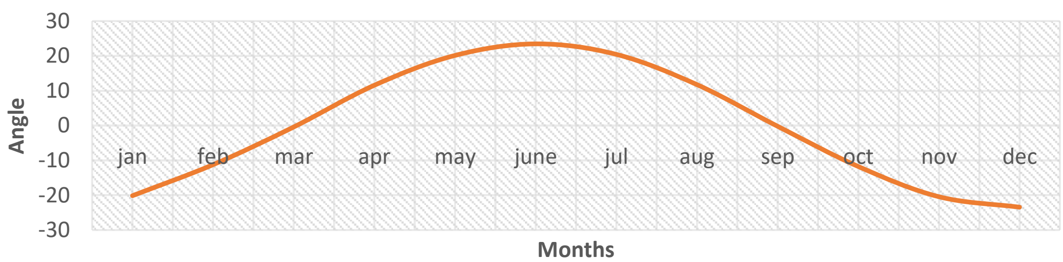

Figure 4. Variation of declination angle throughout the year

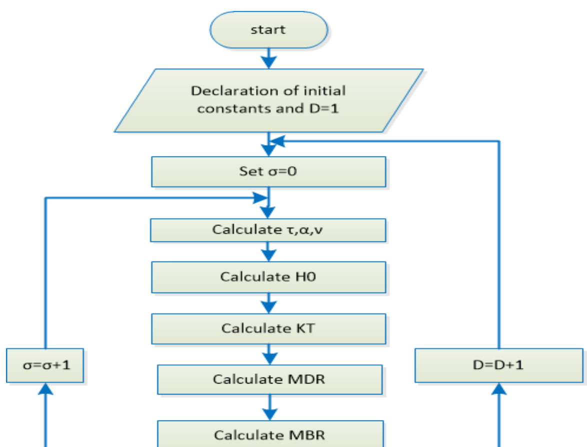

Figure 3. Flowchart for calculation of optimum angle of inclination

The Figure 5 below depicts the variation of H0 (extra-terrestrial radiation in KWh/sq.m./day), HG (monthly avg. daily global horizontal irradiance in KWh/sq.m./day), MBR (monthly avg. daily beam irradiance in KWh/sq.m./day) and MDR (monthly avg. daily diffused radiation by Lui and Jordan empirical model in KWh/sq.m./day) for a year.

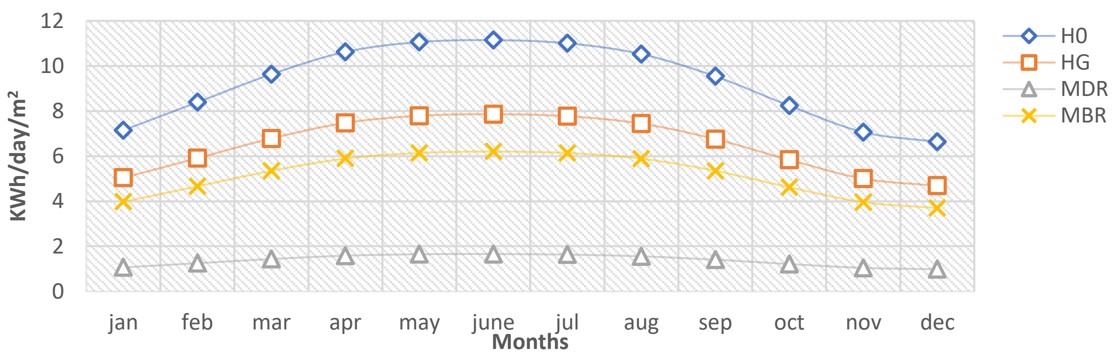

Figure 5. Variation of H0, HG, MBR and MDR (Liu and Jordan) throughout the year

RESULTS AND DISCUSSIONS

The flowchart has been implemented in MATLAB for evaluation of most effective angle of inclination of PV panel on monthly basis. The 21st of each month has been considered for calculation purposes. Daily mean sunshine hours for the area of Chandil have been referred from NASA database. Comparison has been done for four different angles of inclination as $\sigma=0°$, $\sigma=15°$ σ_{opt} and $\sigma=30°$ so as to determine the best inclination for maximum power absorption for every month round the year. The following Table 1 shows various parameters evaluated and σ_{opt} (inclination angle) computed for Chandil.

Table 1. Various evaluated parameters for Chandil

Month	**Day of the year D**	**Angle of declination τ**	**H0 KWh/sq.m./day**	**HG KWh/sq.m./day**	**Optimum angle σ_{opt} °**
January	21	-20.138	7.15	5.04	44.8
February	52	-11.2263	8.39	5.91	37.25
March	80	-0.4037	9.63	6.78	24.75
April	111	11.579	10.62	7.48	4.2
May	141	20.138	11.06	7.79	0
June	172	23.4498	11.14	7.86	0
July	202	20.4415	11.00	7.77	0
August	233	11.7541	10.53	7.44	3.7
September	264	-0.2108	9.54	6.75	24.6
October	294	-11.7541	8.24	5.84	37.8
November	325	-20.4415	7.06	5.00	45
December	355	-23.4498	6.63	4.68	47.35

Input constants has been supplied for computation of various parameters for Chandil. The following Table 2 shows the total solar irradiance evaluated when the angle of inclination is fixed to $\sigma = 0$ ° at different declinations estimated on 21st of every month. Hence maximum radiation is available in the month of June which is 29611.00 KJ/sq.m./day of the summer season. With horizontal PV panels and no inclination, the total amount of energy that can be captured throughout the year is 81.98 KWh/sq.m./day. However, the average value of insolation available is 6.83 KWh/sq.m./day. The Figure 6 presents the variation of various solar insolation levels along with the declination angle throughout the year at $\sigma = 0$ °.

Table 2. Various evaluated parameters at $\sigma = 0$ °

Month	**Day of the year D**	**Angle of declination τ**	**H0 KWh/sq.m./day**	**HG KWh/sq.m./day**	**MBR KWh/sq.m./day**	**MDR KWh/sq.m./day**	**HT KWh/sq.m./day**
January	21	-20.138	7.15	5.04	3.97	1.06	5.27
February	52	-11.2263	8.39	5.91	4.66	1.25	6.19

March	80	-0.4037	9.63	6.78	5.35	1.44	7.10
April	111	11.579	10.62	7.48	5.89	1.58	7.83
May	141	20.138	11.06	7.79	6.14	1.65	8.15
June	172	23.4498	11.14	7.86	6.20	1.66	8.23
July	202	20.4415	11.00	7.77	6.14	1.63	8.13
August	233	11.7541	10.53	7.44	5.89	1.56	7.79
September	264	-0.2108	9.54	6.75	5.35	1.41	7.06
October	294	-11.7541	8.24	5.84	4.62	1.21	6.10
November	325	-20.4415	7.06	5.00	3.96	1.04	5.23
December	355	-23.4498	6.63	4.68	3.70	0.98	4.90

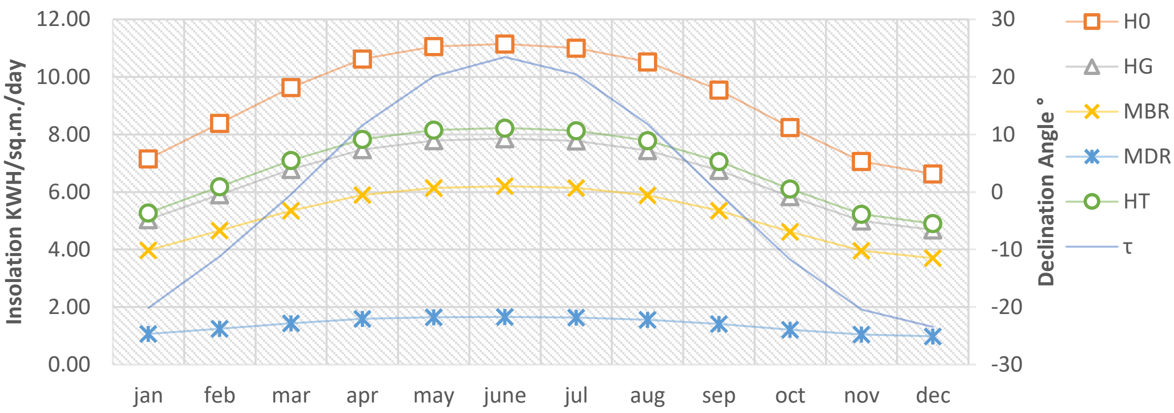

Figure 6. Variation of solar insolation along with the declination angle at σ = 0 °

The angle of inclination has been increased to σ = 15 ° and computation of all insolation levels has been done through the mathematical model discussed in Figure 3. The various parameters that have been evaluated are summarized in the Table 3 below. It can be inferred that maximum radiation is available in the month of April i.e., 27893 KJ/sq.m./day. The total radiation received by the PV plate when inclined at σ = 15 ° is 87.84 KWh/sq.m./day. Meanwhile the average value of insolation is 7.32 KWh/sq.m./day. The Figure 7 presents the variation of solar insolation levels along with the declination angle at σ = 15 °.

Table 3. Various evaluated parameters at σ = 15 °

Month	**Day of the year D**	**Angle of declination τ**	**H0 KWh/sq.m./day**	**HG KWh/sq.m./day**	**MBR KWh/sq.m./day**	**MDR KWh/sq.m./day**	**HT KWh/sq.m./day**
January	21	-20.138	7.15	5.04	3.97	1.06	7.34
February	52	-11.2263	8.39	5.91	4.66	1.25	7.16
March	80	-0.4037	9.63	6.78	5.35	1.44	7.60
April	111	11.579	10.62	7.48	5.89	1.58	7.75

May	141	20.138	11.06	7.79	6.14	1.65	7.65
June	172	23.4498	11.14	7.86	6.20	1.66	7.56
July	202	20.4415	11.00	7.77	6.14	1.63	7.61
August	233	11.7541	10.53	7.44	5.89	1.56	7.70
September	264	-0.2108	9.54	6.75	5.35	1.41	7.55
October	294	-11.7541	8.24	5.84	4.62	1.21	7.09
November	325	-20.4415	7.06	5.00	3.96	1.04	6.54
December	355	-23.4498	6.63	4.68	3.70	0.98	6.30

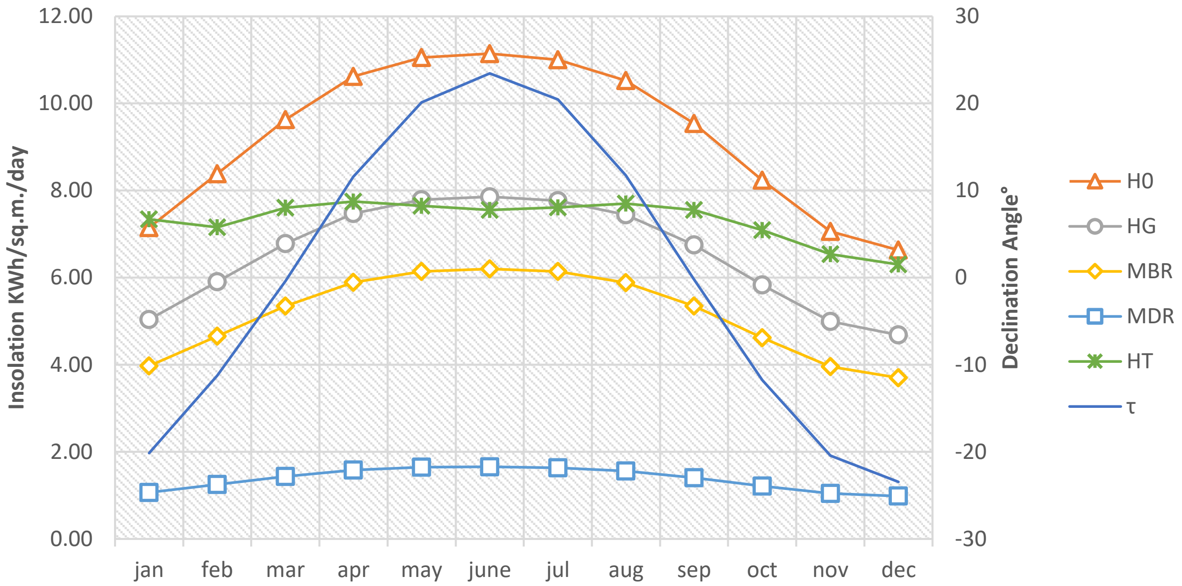

Figure 7. Variation of solar insolation along with the declination angle at σ = 15 °

When the angle of inclination was increased to σ = 30°, various parameters of solar energy evaluated by the algorithm are represented in the table 3 below. The maximum solar energy trapped is in February: 27815 KJ/sq.m./day. The total energy received throughout the year with this arrangement is 87.62 KWh/.sq.m./day, while the average value is 7.30 KWh/sq.m./day. The Figure 8 presents the variation of solar insolation levels along with declination angle at σ = 30 °.

Table 4. Various evaluated parameters at σ = 30 °

Month	**Day of the year D**	**Angle of declination τ**	**H0 KWh/sq.m./day**	**HG KWh/sq.m./day**	**MBR KWh/sq.m./day**	**MDR KWh/sq.m./day**	**HT KWh/sq.m./day**
January	21	-20.138	7.15	5.04	3.97	1.06	7.49
February	52	-11.2263	8.39	5.91	4.66	1.25	7.73
March	80	-0.4037	9.63	6.78	5.35	1.44	7.67
April	111	11.579	10.62	7.48	5.89	1.58	7.27
May	141	20.138	11.06	7.79	6.14	1.65	6.80
June	172	23.4498	11.14	7.86	6.20	1.66	6.57

July	202	20.4415	11.00	7.77	6.14	1.63	6.75
August	233	11.7541	10.53	7.44	5.89	1.56	7.22
September	264	-0.2108	9.54	6.75	5.35	1.41	7.62
October	294	-11.7541	8.24	5.84	4.62	1.21	7.68
November	325	-20.4415	7.06	5.00	3.96	1.04	7.47
December	355	-23.4498	6.63	4.68	3.70	0.98	7.34

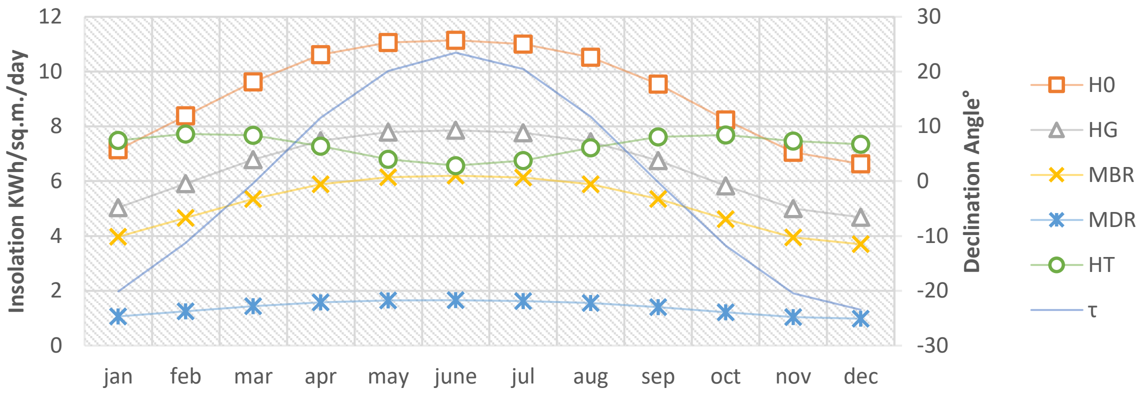

Figure 8. Variation of solar insolation along with the declination angle at σ = 30 °

Utilizing the algorithm, exact value of inclination can be computed for maximum insolation input to the PV panel. The inclination was varied from 0° to 90° with a step size of 0.05° in order to estimate the maximum total solar irradiance and hence precise tilt. This procedure is repeated for every representative day throughout the year. The Table 5 below presents the most effective tilts for PV panel and the corresponding values of solar insolation received. It can be seen that the maximum allowable tilt is of 47.35° in December and the minimum tilt is 0° in May, June and July. These months represents the peak summer in the target area and receives the maximum radiation as compared to other seasons. The maximum energy is captured in June which is 29611 KJ/sq.m./day. The average value of annual energy received is 7.92 KWh/sq.m./day and the total amount received is 95.03 KWh/sq.m./day. Graphical variation of inclination angle along with other parameters is shown in the Figure 9.

Table 5. Various evaluated parameters at $\sigma = \sigma_{opt}$ °

Month	**Day of the year D**	**Angle of declination τ**	**$\sigma = \sigma_{opt}$ °**	**H0 KWh/sq.m./day**	**HG KWh/sq.m./day**	**MBR KWh/sq.m./day**	**MDR KWh/sq.m./day**	**HT KWh/sq.m./day**
January	21	-20.138	44.8	7.15	5.04	3.97	1.06	7.96
February	52	-11.226	37.25	8.39	5.91	4.66	1.25	7.83

March	80	-0.4037	24.75	9.63	6.78	5.35	1.44	7.70
April	111	11.579	4.2	10.62	7.48	5.89	1.58	7.85
May	141	20.138	0	11.06	7.79	6.14	1.65	8.15
June	172	23.449	0	11.14	7.86	6.20	1.66	8.23
July	202	20.441	0	11.00	7.77	6.14	1.63	8.13
August	233	11.754	3.7	10.53	7.44	5.89	1.56	7.80
September	264	-0.2108	24.6	9.54	6.75	5.35	1.41	7.65
October	294	-11.754	37.8	8.24	5.84	4.62	1.21	7.80
November	325	-20.441	45	7.06	5.00	3.96	1.04	7.95
December	355	-23.449	47.35	6.63	4.68	3.70	0.98	7.99

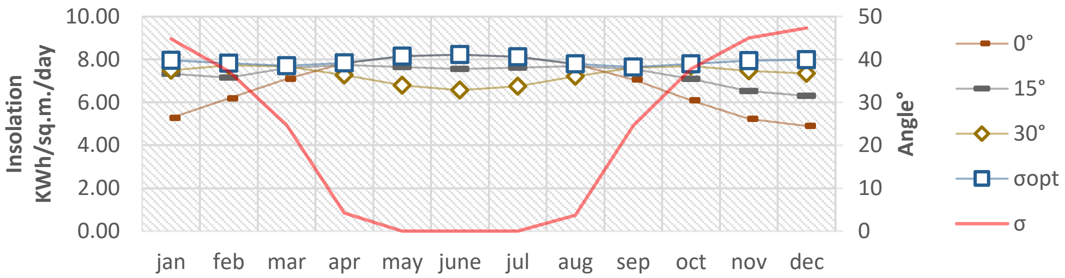

Figure 8. Variation of solar insolation along with the declination angle at $\sigma = \sigma_{opt}$ °

Figure 9 depicts total irradiance computed and different fixed angles of inclination as compared to the optimum angle computed mathematically. On following optimum angle of inclination, maximum energy can be captured in all the seasons round the year. The average value of insolation received after optimization is 7.92 KWh/sq.m./day as compared to 6.83 KWh/sq.m./day with no tilt. Also, the total energy captures after optimization is 95.03 KWh/sq.m./day which is more than 81.98 KWh/sq.m./day for no tilt, 87.84 KWh/sq.m./day for 15° tilt and 87.62 KWh/sq.m./day for 30° tilt. Hence it can be observed that the received energy gets enhanced by 7-13% if the PV panel is inclined to the aforesaid angles.

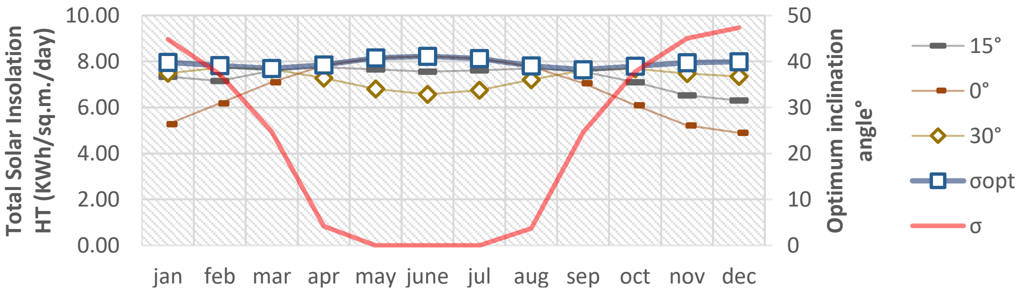

Figure 9. Variation of total solar insolation at different inclination angles along with $\sigma = \sigma_{opt}$ °

CONCLUSION

In this work, a mathematical approach has been utilized to carry out numerical and analytical investigation for maximization of solar insolation being received at Chandil, Jharkhand.

1. The model is developed in the environment of MATLAB/Simulink and necessary constants referred from the NASA database.
2. Most suitable angle of inclination for PV systems to achieve maximum output has been estimated.
3. To acquire the most suitable tilt, the panel angle has been varied from 0° to 90° and corresponding values of total insolation has been computed.
4. The angle providing maximum insolation has been considered as the most promising angle of inclination.
5. Results have been examined for both fixed and variable tilts and month wise suitable inclination angles have been tabulated.
6. Average yearly tilt of PV panel is found to be 22.454° for the target location.

Same procedure can also be employed for insolation estimation and PV system installations at different locations so as to ensure maximum benefit from the most promising, renewable and never lasting source of energy- THE SUN.

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