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Theoretical Gain in Solar Energy for Different Sun Tracking Systems in Delhi

Kanav Vij[1], Rajesh Kumar[2]

Student, Mechanical Production & Industrial and Automotive Engineering Department,
Delhi Technological University, Delhi, India[1]

Assistant Professor, Mechanical Production & Industrial and Automotive Engineering Department,
Delhi Technological University, Delhi, India[2]

Abstract: Solar energy is now one of a major source of energy, which is clean and environmental friendly. The challenge arises to convert solar energy into useful energy using devices. These devices have low conversion efficiency. The seasonal and diurnal movement of earth affects the radiation falling on solar collectors. Sun tracking devices move these collectors to compensate the motion of the earth and maintain the best orientation with respect to sun. In this paper, we have discussed about different tracking systems and their theoretical gain as compared to fixed horizontal system by considering a location as Delhi (ϕ=28.6^o North).

Keywords: solar energy, sun tracking, sunpath, azimuth, gain, cosine.

I. INTRODUCTION

Energy has been universally recognized as one of the most important inputs for economic growth and human development. There is a strong two-way relationship between economic development and energy consumption. On one hand, growth of an economy, with its global competitiveness, hinges on the availability of cost-effective and environmentally benign energy sources, and on the other hand, the level of economic development has been observed to be reliant on the energy demand. One such source of energy can help significantly to meet this surging demand, viz. solar energy. Solar energy is radiant light and heat from the sun. Source of the radiant light and heat energy of the sun is nuclear fusion reaction. The energy due to nuclear fusion reaction taking place at the sun reaches earth by radiative heat transfer. Amount of energy reaching earth is around **1367 W/m^2** (Solar Constant). Solar radiation is energy in the form of electromagnetic radiation which are characterized by wavelengths and frequencies. Use of solar energy requires devices to extract energy and use it for different applications. These devices are also known as solar collectors. Alternative renewable energy sources such as sun energy can be substituted for exceeding human energy needs. Covering 0.16% of the land on earth with 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy [1].

A. Nomenclature

β = inclination of plane
ϕ = Latitude position of site
δ = Declination of earth
γ = surface azimuth angle of plane
γ_s = solar azimuth angle
ω = hour angle
θ = angle of incidence
θ_z= zenith angle
α = solar altitude angle
I_{rr} = irradiation received
C = cosine factor

II. TRACKING

Searching for clean energy sources is one of the biggest challenges for society. Even availability of energy is not sufficient, but, to make the available energy sustainable is major challenge. Solar Energy, one of alternative renewable energy source, can substitute the human energy needs. The potential for solar energy is enormous, with covering just 0.16% of land on earth and using 10% efficient solar energy conversion device, 20TW of power can be generated, which is nearly double the power required by the world [2]. But, solar energy falling on a surface is not constant because of movement of the sun in sky.

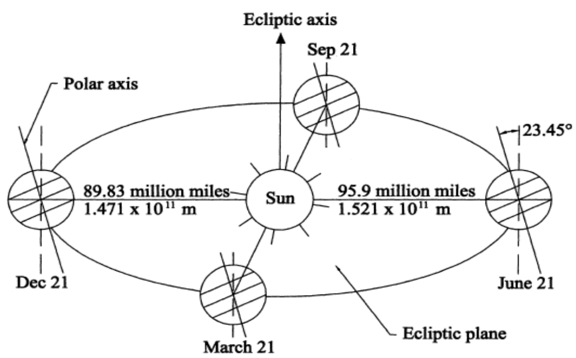

Figure 1: Motion of Earth about sun

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The earth revolves around the sun, the orbit of revolution is elliptical in shape, with sun at one of the foci. The time taken by the earth to complete one revolution of its orbit defines a year. The plane in which earth's orbit is part of, is known as elliptic plane. With revolution around the sun, earth is also rotating about its own axis. Earth's axis is tilted by 23.45^o to the axis of elliptic plane. The angle made by; a line joining the centers of earth and sun and the equatorial plane of earth is called **declination angle (δ).**

As shown in Figure 1, declination angle changes from -23.45^o on December 21st (also known as winter solstice) to +23.45^o on June 21st (also known as summer solstice). Declination angle is zero on March 21st (venal) and September 21st (autumnal), these days are known as equinoxes. As the earth rotates about its own axis, the instantaneous position of sun can be described by **hour angle (ω)**. Hour angle is angle between meridian passing through sun and the meridian of location or site of study. Hour angle is zero when meridian passing through sun is same as that of the site, this time is known as solar noon. Hour angle is negative before solar noon viz. when sun is rising in the East and it is positive after solar noon, in the west. Rate of change of hour angle (ω) is 15^o per hour.

To define any location of site on earth's surface, one needs two parameters, those are **latitude (ϕ)** and longitude of that location. Latitude is a geographic coordinate defined by an angle between a radial line made by joining the point of site and the centre of earth and plane of equator. Lines of constant latitude, also known as parallels run from east to west. The range of latitude is 0^o for equator, $+90^o$ for North Pole and -90^o for South Pole. Longitudes are meridian lines running from the North Pole to the South Pole. The intersection of longitudes and latitudes will give location of any site on earth's surface. Latitude have importance to understand the movement of sun.

III. ANGLES FOR TRACKING SURFACE

There are several angles to describe position of the sun relative to any plane situated at any point on surface of the earth. The plane can be fixed or moving (in case of tracking).

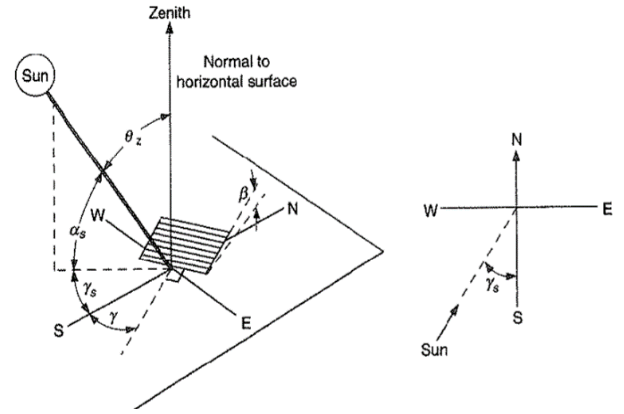


Figure 2: Schematic representation of the solar angles

These angles will help us understand the motion of sun which will give direction of beam (or direct) radiation. Beam radiation have major role in working of any solar technology and without beam radiation no concentrated solar technology will work. For a tracking system, sun direction is necessary because surface has track the sun directly.

Following are some of important angles to describe sun's position with respect to any plane on earth's surface:

Figure 2 represents few angles to describe position of sun with respect to any plane or surface.

ϕ = **Latitude**, Location of a point on a surface, described by angle. $-90^o \le \phi \le 90^o$.

δ = **Declination**, The angle made by; a line joining the centers of earth and sun and the equatorial plane of earth, $-23.45^o \le \delta \le 23.45^o$.

β = **Slope of surface**, it is the angle between surface plane and the horizontal surface at that location. $0^o \le \beta \le 180^o$

γ = **Surface azimuth angle**, made by projection of normal of plane on horizontal surface and local meridian. Ranges from $-180^o \le \gamma \le 180^o$ with south as zero, east negative and west positive.

ω = **Hour angle** is angle between meridian passing through sun and the meridian of location or site of study

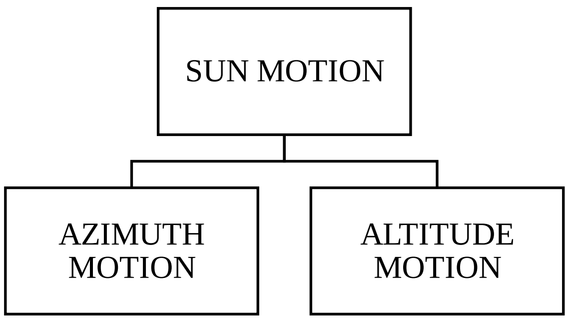
θ = **Incident angle**, angle between normal of surface and beam radiation.

θ_z= **Zenith angle**, angle made by a vertical line at location and the beam radiation.

α_s = **Sun Altitude angle**, angle between beam radiation and horizontal surface

γ_s = **Sun azimuth angle**, it is the angle made by local meridian and projection of beam radiation on a horizontal plane or deviation of the projection from south direction. East is negative and west is positive.

The sun motion is divided in two directions; first is **Azimuth motion** and **Altitude Motion**. In the following relationships, we will know the details of each azimuth and altitude motion.



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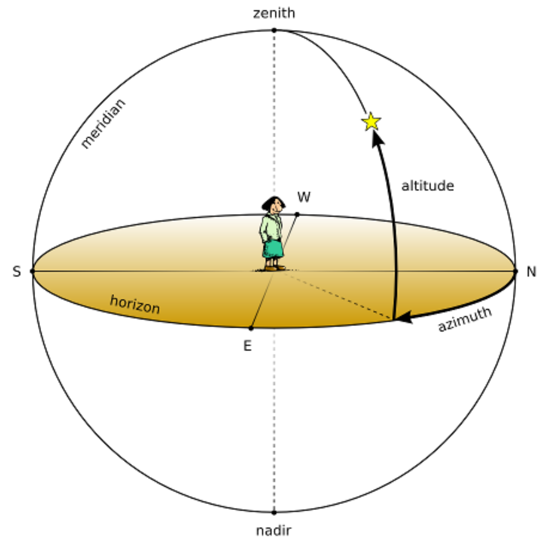

Figure 3: azimuth and altitude for a coordinate on earth.

A. Important Relations

We know that earth revolves around the sun, on its elliptic orbit. But to study angles, we assume that earth is stationary and relatively sun moves. Before proceeding with the study, there are few trigonometric relations relating earth's movement with respect to sun. These relations are important because sun's position changes with respect to a point located on earth and therefore changes energy input to the collector surface [3]. Declination angle can be found from the following relationship:

$$\mathbf{\sin\delta = \sin(23.45)\sin[360\,\frac{(284+n)}{365}]} \qquad \text{(A)}$$

Where n is the day number during a year with January 1 being n=1

$$\begin{aligned}\mathbf{\cos\theta = } & \mathbf{\sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma} \\ & \mathbf{+ \cos\delta\cos\phi\cos\beta\cos\omega} \\ & \mathbf{+ \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega} \\ & \mathbf{+ \cos\delta\sin\beta\sin\gamma\sin\omega}\end{aligned} \qquad \mathbf{(1)}$$

From equation (1), we can see that, incident angle (θ) is a function of day (n), on which we are observing, location (ϕ) of site, angles of plane (β and γ) and hour angle (ω). Hour angle changes at 15^o/hr. For a particular day, sunrise and sunset time is determined as:

$\cos\omega = -(\tan\phi\tan\delta)$ (sunrise)

$\cos\omega = (\tan\phi\tan\delta)$ (sunset)

Hour angle also helps to determine the length of day. At solar noon, hour angle is zero.

B. Variation of Solar Altitude and Solar Azimuth Angle With Respect to Hour Angle

Solar elevation and solar azimuth angle give us information about the position of sun in sky as viewed from a point on earth. To track sun we should know these angles. These angles act as guides for tracking systems.

$$\sin\alpha = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \qquad (2)$$

$$\cos\gamma_s = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi} \qquad (3)$$

C. Energy estimation on a surface

Cosine Factor (C)

$$= \frac{\text{Direct radiation received perpendicular to the surface (D)}}{\text{Incoming Radiation (Irr)}}$$

Energy for small fraction of time

$$\begin{aligned} = & \text{(Cosine factor)} \\ & * \text{(incoming direct radiation from sun)} \\ & * \text{(small interval of time)}\end{aligned}$$

$$\text{Insolation} = \int_{t1}^{t2} C.\,Irr.\,dt \qquad (4)$$

Where t1 and t2 are sunrise and sunset time, dt is small change in time. This small change in time is proportional to hour angle and t1 and t2 can be written as in terms of hour angle. Assuming irradiation (I_{rr}) to be constant. After integration we get the value of insolation for a particular day.

Therefore, equation (4) can be written as:

$$\text{Insolation} = \int_{\omega1}^{\omega2} C.\,Irr.\,d\omega$$

$$= Irr\int_{\omega1}^{\omega2} C.\,d\omega$$

$\int_{\omega1}^{\omega2} C.\,d\omega$ Gives the value of equivalent sunshine hours for a day.

Direct radiation (D) collected by any surface is given by the product of cosine factor (C) and incoming solar radiations (I_{rr}). The value calculated will be a theoretical maximum value for a particular day. Practical value of radiation received by a surface depends on various atmospheric conditions. To know the benefit of using tracking system, we will compare theoretical values for each tracking arrangements.

IV. SUNPATH

Sun path is a path followed by sun in sky, with hourly and seasonal variations in its position. As earth rotates the sun apparently travels in sky and with revolution of earth around sun, seasonal variations occur. A diagram made of curve showing sun's position i.e. solar azimuth and solar altitude, is known as sunpath diagram. Sunpath diagram is also known as solar position plot. Sun path finder is a device which is used to trace these curves, however, these curves can be plotted on MATLAB or Excel from the relations discussed above. The position of sun is an important factor to evaluate heat gain for a building and performance analysis of solar energy technologies. Knowledge of sunpath and local climatic conditions are necessary inputs to make economic decisions for any solar energy technology. Sunpath is not

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just necessary for tracking systems, it is also necessary for fixed systems for which shadow analysis is crucial [4].
Sunpath acts as the guiding path for the tracker. Therefore, solar tracker should follow the sunpath in order to receive maximum radiation. The actual movement for solar tracker is different for its application. For example, solar tracker used for photovoltaics follows sunpath completely; but for heliostat mirror, the tracker follows different path which depends on its position in the field and height of the tower. Due to this fact, it becomes necessary to use tracking mechanism for heliostats. Sunpath diagrams are also used in passive air-conditioning design, to reduce the direct radiation by the help of shades. Sunpath diagram for each can be drawn in MATLAB, using relations (1) and (2). A script file was created to draw sunpath for a particular day. **Error! Reference source not found.** Shows the sunpath for Delhi (ϕ=28.6^o), for summer and winter solstice, i.e. 21st of June and 21st of December.

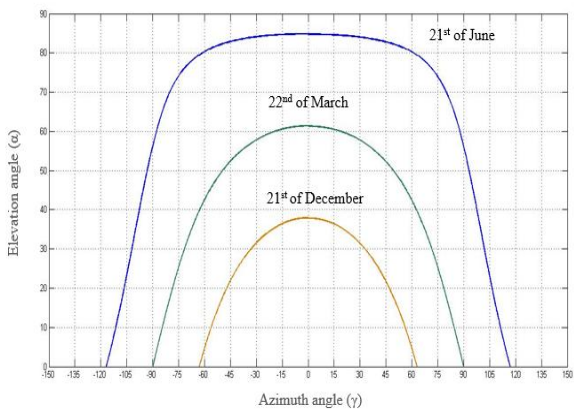

Figure 4: Sunpath diagram for Delhi (ϕ = 28.6^o)

V. SUN-TRACKING DRIVING METHODS

Solar trackers require external driving force to track the sun. There are three driving methods used to track sun:

A. Passive Trackers
Passive solar trackers work on the principle of thermal expansion. The driving material could be a gas or a metal. When gases are heated, the pressure increases and this rise in pressure drives the solar tracker. Two gas cylinders are placed against each other, when sunlight falls on any one of the cylinder, the thermal energy in solar radiation raises the temperature of the gas, a pressure difference is created and tracker moves with the path of sun [5]. Shape Memory alloys are sensitive to temperature, when they are heated they form different shape. This sensitive material can also be used to drive tracking system. Passive trackers do not require external power source to operate, but, their only drawback is that they are sensitive to irradiation, which always varies due to local weather conditions such as clouds.

B. Active Trackers
Active sun trackers are categorized as optical sensor and microprocessor based, chronological data based and an auxiliary bifacial solar cell based systems. Active trackers follow the sun actively with the help of low speed motors (called actuators). The actuators can be guided by a optical sensor or by a program based on dates (chronological inputs). Active system require an external source of power to operate them. Advantage of active trackers over passive trackers is that, these are very accurate, their working does not depend on weather conditions, and their structure is solid.

VI. TYPES OF SUN TRACKING

We have seen that sun uniformly travels in sky, or it changes its apparent position with respect to earth. This change affects the energy captured by any solar energy device (cosine effect). To minimize this loss of energy, solar energy collectors have an integrated arrangement to track the sun's apparent position. The principle to maximize beam radiation is by minimizing the angle of incidence (θ). These integrated devices are called sun trackers. Though these tracking arrangements have some drawbacks, such as, require external power to drive the tracking mechanism, require maintenance. But, the benefit of using these systems is economical. In this section, we will understand different types of tracking systems classified by their motions, also we will know the benefit of using each tracking systems.

A. Single Axis Tracking
In this type of tracking systems, the orientation of the collector (surface) is changed about a single axis, therefore, in this system, only one parameter is required to control movement of the collector to get maximum incident radiation. These systems are widely used with large photovoltaic plants and concentrated collectors. Concentrated solar thermal technology; linear Fresnel collector and parabolic trough collectors use single axis tracking systems. From relations (2) and (3) it can be seen that there are two sun angles viz. sun azimuth angle and sun altitude angle, so we can control any one angle. Based on the angle controlled, single axis tracking is divided in two categories [6]:

1.) North South Tracking:

Figure 5: North South tracking surface.

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In this type of single axis tracking system, the movement of collecting surface is adjusted by rotating the surface about an axis which is drawn from North to South of that location or the normal drawn to collector surface is rotated about a NS line, however the axis can be parallel or inclined to the N-S axis. Sun azimuth angle (γ_s) is tracked continuously for a day to get the maximum input of direct solar radiations. Cosine factor for NS tracking surface is given by the following relationship:

$$C = \sqrt{(\cos^2 \theta z + \cos^2 \delta \sin^2 \omega)} \qquad (5)$$

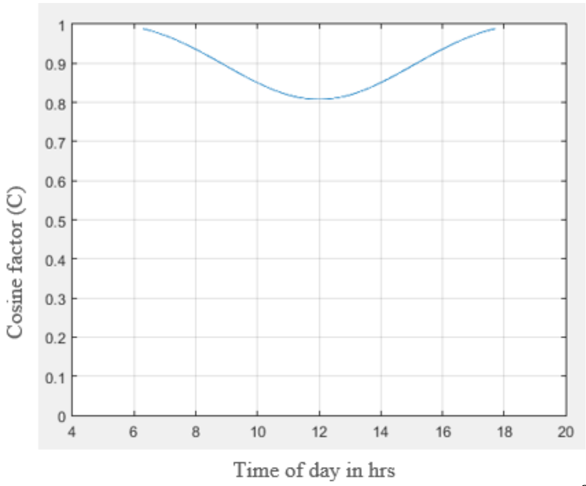

Figure 6: cosine curve for N-S tracked surface (ϕ = 28.6^o)

A curve (figure 6) of equation (5) is drawn in MATLAB to show an example of cosine factor, location selected is Delhi (ϕ=28.6^o), date is 10th of October. Area under this curve will give us equivalent sunshine hours for that day. Area can also be found by integrating the equation with respect to hour angle. By evaluating the curve for each day and calculating the sunshine hours for each day, for a complete year we add all the values for different days, therefore, we get total equivalent sunshine hours =3972 hrs.

2.) East West Tracking:
In this type of tracking system, the movement of collecting surface is adjusted by rotating the surface about an axis which is drawn from East to West of that location. The normal of plane rotates about E-W axis. Altitude angle (α) is tracked to get maximum input.

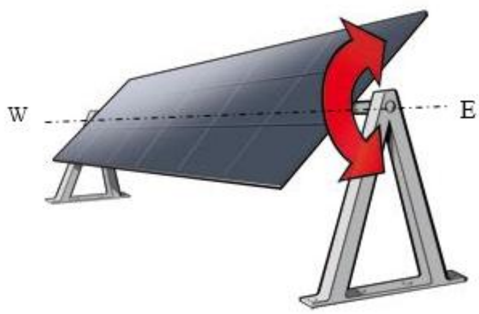

Figure 7: East West tracking surface.

The adjustment can be made in two ways:

a. Daily single adjustment:
The collector surface is rotated about horizontal east-west axis with a single daily adjustment so that the beam radiation is normal to the surface at solar noon each day. Cosine factor for EW single daily tracking surface is given by the following relationship:

$$C = \sin^2 \delta + \cos^2 \delta \cos \omega \qquad (6)$$

b. Daily continuous adjustment:
The collector surface is rotated about horizontal east-west axis with continuous adjustment. Cosine factor for EW daily continuous tracking surface is given by the following relationship:

$$C = (1 - \cos^2 \delta \sin^2 \omega)^{1/2} \qquad (7)$$

A plot of curve (7) for date 10th October for Delhi (ϕ=28.6^o) is shown in figure 8.

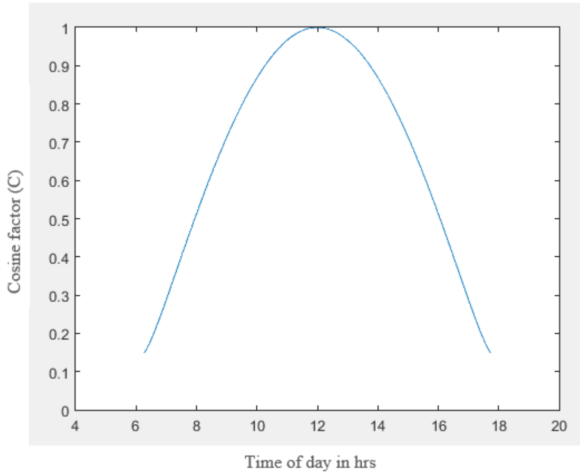

Figure 8: Cosine curve for E-W tracked surface (ϕ=28.6^o)

Area under this curve will give us equivalent sunshine hours for that day. Area can also be calculated by integrating the equation with respect to hour angle. By plotting the curve for each day and calculating the sunshine hours for each day, for a complete year we add all the values for different days, therefore, we get total equivalent sunshine hours =3016.3 hrs.

B. Two Axis Tracking:
Two axis tracking system involves tracking the sun's movement completely. The tracking system has to track both the motion of sun viz. Azimuth motion and altitude motion. For this tracking, two actuators are used to control the motion of system in two axis. Therefore, this system is also known as 2 degree of freedom tracking. For these systems, cosine factor is always unity.

$$C = 1$$

For this type of tracking we get a straight line ideally and maximum sunshine hours is equal to sun hours for that particular day. For a complete year we add all the values for different days and we get total sunshine hours= 4380 hrs.

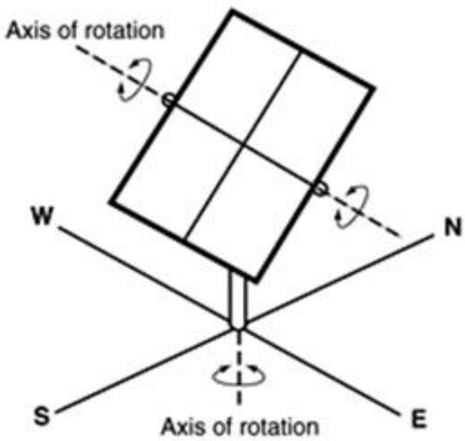

Figure 9: dual axis tracking

VII. GAIN IN ENERGY BY USING TRACKING SYSTEMS (A CASE STUDY OF DELHI)

A case study is done for Delhi (latitude location 28.6^o north). A comparison of different tracking systems stated above is done graphically to know the advantage of tracking systems over fixed mounted systems. This comparison study does not include any losses due to atmosphere reflection and absorption nor loss due to weather conditions. Therefore, this study is just ideal case study and compare the maximum availability of sun for a particular location with different system arrangements (tracking systems). Figure 10, shows a plot made by evaluating ideal energy output for each day, for each tracking system with equivalent sunshine hours on y-axis and months on x-axis.

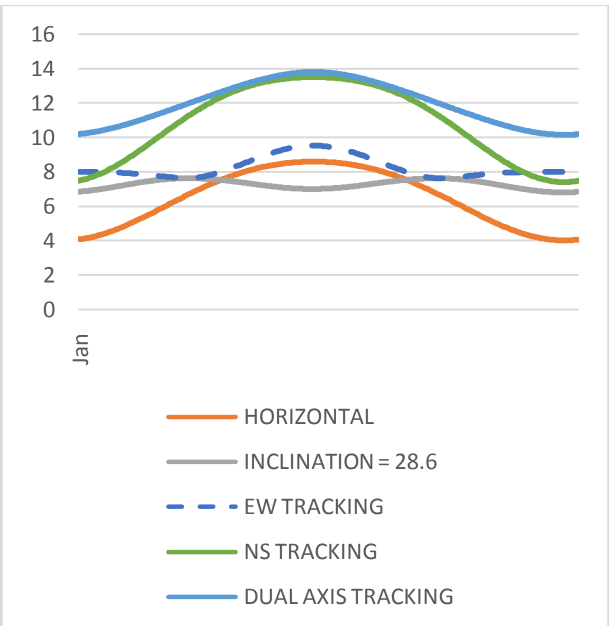

Figure 10: A comparison of output of different tracking systems for Delhi (ϕ=28.6)

VIII. CONCLUSION

We have discussed about different tracking situations for a particular location (Delhi, ϕ=28.6^o). The study done is for ideal case in which no weather conditions are considered. We have calculated equivalent sunshine hours for a year for each tracking arrangement. For dual axis tracking, equivalent sunshine hours were equal to 4380, therefore, maximum capacity factor is 50%. For single axis, N-S tracking arrangement, equivalent sunshine hours is 3972, capacity factor is 45.3%. For single axis, E-W tracking arrangement, Equivalent sunshine hours is 3016.3, capacity factor is 34.4%. For a plane inclined at an angle equal to latitude (ϕ=28.6^o), equivalent sunshine hours are 2656.8, capacity factor is 30.3%. For a horizontal plane, equivalent sunshine hours are 2379, capacity factor is 27.1%. Therefore, we can say by comparing each arrangement with horizontal arrangement; dual axis arrangement has 84.11% more output; N-S tracking arrangement has 67% more output; E-W tracking has 26.7% more output. These calculations are purely for ideal case. The output for solar energy largely depends on location (ϕ) and local weather conditions.

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