# Modelling and Estimation of Photosynthetically Active Solar Radiation in an Agrivoltaic Plant in New Delhi

**Subhra Das**
Solar Engineering Department, Amity School of Engineering and Technology, Amity University

## Abstract

The objective of the present work is to develop a model to estimate the photosynthetically active radiation (PAR) under a solar photovoltaic panel located in New Delhi. The proposed model utilises only the location parameter along with day of the year and time to predict the instantaneous total and diffuse PAR, monthly average hourly PAR and monthly average daily PAR values. The result is compared with those reported in the literature which shows considerable agreement in the result for the winter, summer and monsoon months for the peak value of PAR. The total PAR varies between 0.5- 463W/m$^2$ and the diffuse PAR varies between 24.8- 125.7W/m$^2$over the year.
**Keywords***:* Agro-voltaic, PAR, Decomposition model, Sustainable Agriculture

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## Introduction

With the proliferation of solar energy generation in India, people have started taking interest in combining farming with solar photovoltaic power generation. The objective of this paper is to estimate the solar radiation under a ground mounted solar photovoltaic plant located in New Delhi and thereby estimate the photosynthetically active solar radiation under the solar panels. Mathematical models are proposed to estimate the instantaneous total and diffuse PAR, monthly average hourly and daily total PAR and monthly average hourly diffuse PAR.

Small and marginalized farmers in India are unable to earn enough money from the agriproducts and are selling off their land and taking up other secure job roles to earn money for their livings. This is leading to loss of agricultural land and loss of skilled manpower ( farmers) whose knowledge and skills goes a waste as they move into some other profession. Now, the Government of India has provided a solution to the farmers to increase their revenue from the same piece of land under the KUSUM scheme by combining solar PV power generation with agriculture(Pulipaka et al. 2021). As per the scheme farmers can install solar PV power plant in their agricultural field which can be installed at a height of 3 ft above the ground so that the land can be utilized for farming. Sandbox Solar, founded by Ian Skor, PE, has developed an agri-voltaic software modelling tool to optimize the design of collocated solar PV with crops. Agri-voltaic is seen to be a technology which can increase the revenue of the farmers from the same piece of land over the entire year. There are three different layouts of the AVPs based on the arrangement of solar panels and agricultural area (Pulipaka et al. 2021). The first one is the interspace farming wherein crops are grown in the space between two rows of solar arrays. The second type is farming below the panels which are installed with a tilt angle equal to the latitude and no special arrangement is made for growing crops underneath these panels. Manual cultivation is only possible under these panels. The third type is the farming below elevated structures which are around 3m high (Casares de la Torre et. al. 2022). The elevation enables farmers to use machineries for farming and allow sunlight to uniformly spread over the land area. As per the available literature there are sixteen operational agri-voltaic plants in India (Das 2022) scaling from 1 MW agri-voltaic plant at GPCIL Amrol Gujrat to 7 kW at Junagadh Agricultural University.

The major challenges that one faces while growing crops underneath the solar panels is of the availability of solar radiation. Mathematical relations were derived to calculate the fraction of light that reach the ground under the collector field when collectors are mounted 2m above the ground with row


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spacing equal to three times the height of the collectors (Goetzberger et al. 1982).
Trommsdorff et al. 2022 proposed two categories of agri-voltaic plants viz. Category I- Overhead PV with vertical clearance > 2.1 m and Farming under the agri-voltaic system Category II- Interspace PV with vertical clearance < 2.1 m and Farming between the rows of agri-voltaic systems.
Solar radiation is the main source of energy for all natural processes especially photosynthesis and solar PV performance (Oliphant and Stoy, 2018; Norman and Welles, 1983) Analogous to solar PV system, plants use solar radiation in the wavelength of 400-700 nm for photosynthesis. This component of the solar radiation is known as photosynthetically active radiation (PAR). Quantum sensors are utilised for measuring PAR at any site. But it is difficult to have a ground measured PAR data for all sites which can be utilized for decision making for the selection of plants that can be grown in the given site. Ghayas et al. (2022) reported that long term study of PAR for Indian region is not available because of the absence of dedicated sensor network for regular measurement of PAR over Indian regions. They have conducted a study to measure PAR for Delhi for four years starting from 2013 to 2016.These calls for the requirement of models to predict PAR for Indian regions. The present work will focus on developing a model to estimate PAR for New Delhi.
Gardea (2020) presented a review of the empirical models developed by researchers across the globe to estimate PAR. $PAR_{total}$ is estimated using various parameters like global solar radiation, solar elevation angle, clearness index, aerosol optical depth to name a few. Salim et al.(2014) developed a non-reproducible model to estimate PAR at Dehradun, India. Researchers have proposed decomposition models to estimate $PAR_{diffuse}$ as a function of parameters like clearness index, diffuse fraction, solar elevation, $PAR_{total}$ and these models are compared to check their accuracy in estimating $PAR_{diffuse}$ (Lu et al. 2022). Decomposition models are found to be useful in the absence of on-site diffuse measurements. It is used to predict diffuse horizontal irradiance at any arbitrary locations, which can be further utilised to estimate $PAR_{diffuse}$. Lu et al. (2022) compared seven stand-alone decomposition models and an EMOS approach model for global horizontal radiation which is used to estimate PAR.

## Proposed Model

In an Agri voltaic system decomposition of photosynthetically active solar radiation into diffuse and direct component is essential because of the shading caused by the solar panels which shows seasonal and diurnal variation. The diffuse and total PAR values are computed using the following steps:

**Step 1: Estimate instantaneous extraterrestrial radiation on a horizontal surface having a wavelength between 400- 700nm.**

The extraterrestrial radiation on a horizontal surface is given by (Duffie and Beckman,:

$$G_o = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)\cos\theta_z \quad (1)$$

where Gsc = 1367 W/m2 is the solar constant, n is the day of the year and is $\theta_z$the zenith angle. As per the World Radiation Centre spectrum (Duffie & Beckman, ) the fraction$f_{0-\lambda}$ of the total energy in the spectrum that lies between wavelengths zero and 400nm is 0.080 and $f_{0-700nm} = 0.469$.
Therefore, the fraction of the total spectrum that lies between 400-700nm is given by:

$$f_{400-700nm} = 0.469 - 0.080 = 0.389 \quad (2)$$

Thus, the extraterrestrial radiation($PAR_{ext}$) incident on a horizontal surface having a wavelength between 400-700nm is given by:

$$PAR_{ext} = G_o \times f_{400-700nm} \quad (3)$$

**Step 2: Estimate instantaneous Photosynthetically Active Radiation on a horizontal surface on the earth surface.**

The fraction of extraterrestrial radiation that reaches the earth surface on completely clear and overcast day at an altitude of up to 300m is denoted by f= a+ b where the parameters a and b depends on altitude of the place and month of the year (Rahman et al. 2013). The values of a and b are tabulated in Table 1.

**Tab 1: The values of the parameter a and b for computing the fraction of extraterrestrial radiation reaching the earth surface (Rahman et al.** 2013)

| **For altitude up to 300 m** | **January, February, December** | **March, April, May** | **June, July, August** | **September, October, November** |
|---|---|---|---|---|
| **a** | 0.18 | 0.21 | 0.25 | 0.25 |
| **b** | 0.51 | 0.49 | 0.51 | 0.51 |

Therefore, the radiation reaching the earth surface on a horizontal plane having a wavelength between 400-700nm is given by:

$$PAR_{total} = f \times PAR_{ext} \quad (4)$$

**Step 3: Estimating monthly average hourly PAR on a horizontal surface**

The monthly average hourly extraterrestrial radiation on a horizontal surface (kJ/m$^2$h) can be calculated using the following two relations reported in literature Duffie (2013) and Sukhatme (2012) respectively**:**

$$I_{o1} = \frac{12\times3600}{\pi} G_{sc}\left[1 + 0.033\, cos\, \left(\frac{360n}{365}\right)\right] \times \left[\cos\varphi\cos\delta\,(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180}\sin\varphi\sin\delta\right] \quad (5)$$

$$I_{o2} = G_{sc}\left[1 + 0.033\, cos\, \left(\frac{360n}{365}\right)\right](sin\,\varphi\, sin\,\delta + cos\,\varphi\, cos\,\delta\, cos\,\omega \quad (6)$$

where $G_{sc}$= 1.367kW/m$^2$, φ is the latitude of the place, δ is the declination angle, ω is the hour angle and n is the day of the year.

The monthly average hourly PAR on a horizontal surface ($\overline{PAR}_H$) can be calculated using the following relation:

$$\overline{PAR}_{H,j} = f \times I_{oj} \;\; ; j = 1,2. \quad (7)$$

**Step 4: Estimating monthly average daily PAR on a horizontal surface**

The monthly average of daily extraterrestrial radiation$\overline{H}_o$ on horizontal surface (kJ/m$^2$-day) can be calculated using the relation Duffie (2013):

$$H_o = [24\, I_{sc}(1 + 0.033\cos\left(\frac{360n}{365}\right))\{\omega_s\sin\varphi\sin\delta + \cos\varphi\cos\delta\sin\omega_s\}]/\pi \quad (8)$$

Here $\omega_s$ is the sunset hour angle. Klein (1977) determined that the value of $H_o$ is equal to $\overline{H}_o$ on January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14 and December 10.

The monthly average daily PAR on a horizontal surface can be calculated using the following relation:

$$\overline{PAR}_D = f \times I_{oj} \;\; ; j = 1,2. \quad (9)$$

**Step 5: Estimate diffuse PAR on a horizontal surface**

Lu et al. (2022) calculated $PAR_{diffuse}$ as a function of diffuse fraction and solar elevation angle using decomposition method.

$$k_{d,PAR} = \frac{PAR_{diffuse}}{PAR_{total}} = \frac{[1+0.3(1-k_d{}^2)]k_d}{1+\left(1-k_d{}^2\right)cos^2\,(90-\alpha)\cos^3\alpha} \quad (10)$$

Here $k_d$= DHI/ GHI is the diffuse fraction where DHI and GHI are respectively the diffuse and global horizontal irradiance (W/m$^2$), and $\alpha$ is solar elevation angle measured in degree. The ASHRAE model can be used to compute DHI and GHI.

**Step 6: Estimate the area between the panels which will receive total PAR and diffuse PAR**

Estimation of the length of the shadow

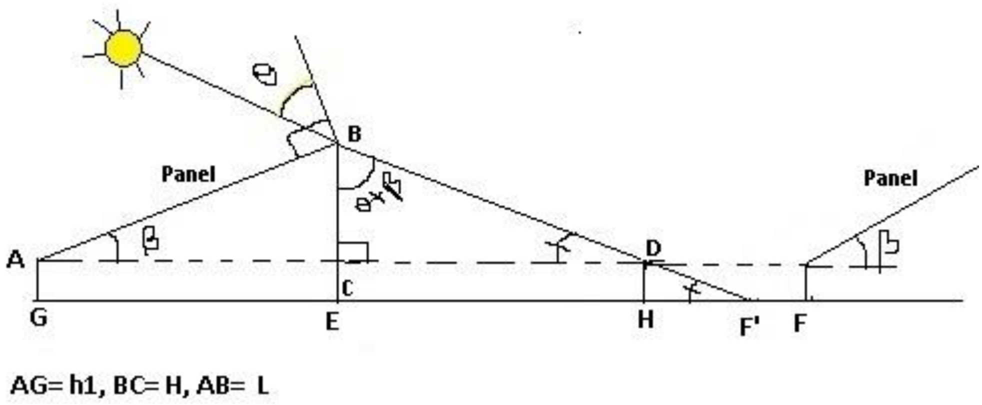


**Fig 1: Shadow Analysis**

The plants can be grown under the panels (region GE) and in the inter row spacings i.e EF region as shown in Fig1. The region GE is always under shadow but length of the shadow EF' in the EF region changes over the day and shows seasonal variation as well. The distance between two panels EF is calculated based on the day on which the panel will cast the longest shadow i.e. corresponding to the winter solstice.

Form $\Delta ABC$ we get,

$$AC = AB\cos\beta = L\cos\beta \quad (11)$$

The length of the shadow (D=CD+ HF') that the panel will cast on the ground in the region EF is calculated from $\Delta BCD$. And $\Delta DHF$ as

$$CD = L[\sin\beta\,/\tan(90° - \theta - \beta)] \quad (12)$$

$$HF' = [h_1\,/\tan(90° - \theta - \beta)] \quad (13)$$

where L is the length of the panel AB, $\beta$ is the tilt angle of the panel, $\theta$ is the angle of incidence of the beam radiation on the tilted panel at any time of the day and $h_1$ is the height AG at which the panel is installed. The length of the shadow in the inter row spacings vary over the day and shows seasonal variation.

Thus, on a particular day the plants which are grown under the panel will receive diffuse radiation throughout the day. On the other hand, plants grown in the inter row spacings will receive both beam and diffuse radiation based on the time and day of the year. Beam radiation will be in the region F'F and diffuse radiation will be in the region GF'.

## Results and Discussions

In this work, a ground mounted solar PV power plant is stuided which is installed at New Delhi (28°35' N, 77°12'E) having an average of 8.6 h of sunshine hours per day. The dimensions (length x breadth x thickness ) of the modules used in the plant is 197.6 x 99.2 x 3.5 cm and are tilted at an angle of 30° with the horizontal. Applying the proposed model, the photosyntheically active solar radiation is estimated for the entire year.

The analytical modelling of Photosynthetically Active Radiation is conducted using the formultaion described above. The instantenous extrateresstrial radiation having a wavelength between 400-700nm ($PAR_{ext}$) is calculated for the entire year and is shown in Fig 2. It has been observed that the mean $PAR_{ext}$ is 236.4±170 W/m$^2$ for the entire year. Consequently, $PAR_{total}$ incident on a horizontal surface in New Delhi vary between 0.5- 463 W/m$^2$ having a mean equal to 172 ±123 W/m$^2$ for the year.

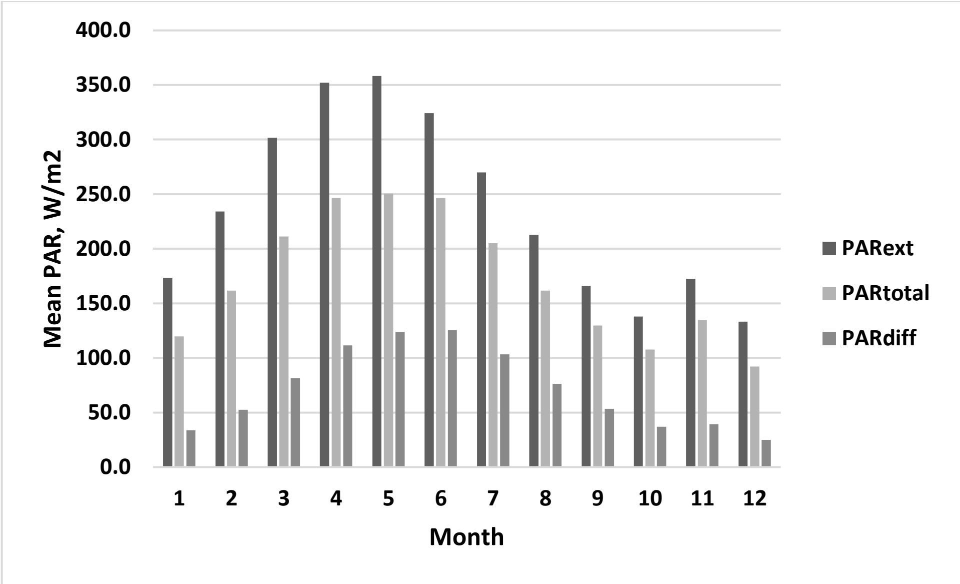


**Fig 2: Monthly average of Instanteneous extraterrestrial radiation having a wavelength between 400-700nm, total and diffuse PAR incident on a horizontal surface at New Delhi..**

The monthly average hourly PAR is calculated using equations (5-7) on a horizontal surface located in New Delhi and is shown in fig 3. The average, range and standard deviation of these values were calculated for the entire year. It is observed that mean $\overline{PAR}_{H,1}$ = 667±175 kJ/m$^2$h, having a range of 397-912 kJ/m$^2$h for the entire year. The PAR values computed using eq.6 gives the mean equal to 604±147 kJ/m$^2$h, having a range of 372- 810 kJ/m$^2$h for the entire year. There is a 8.8% difference in the value of $\overline{PAR}_H$ computed using formula 5 and 6.

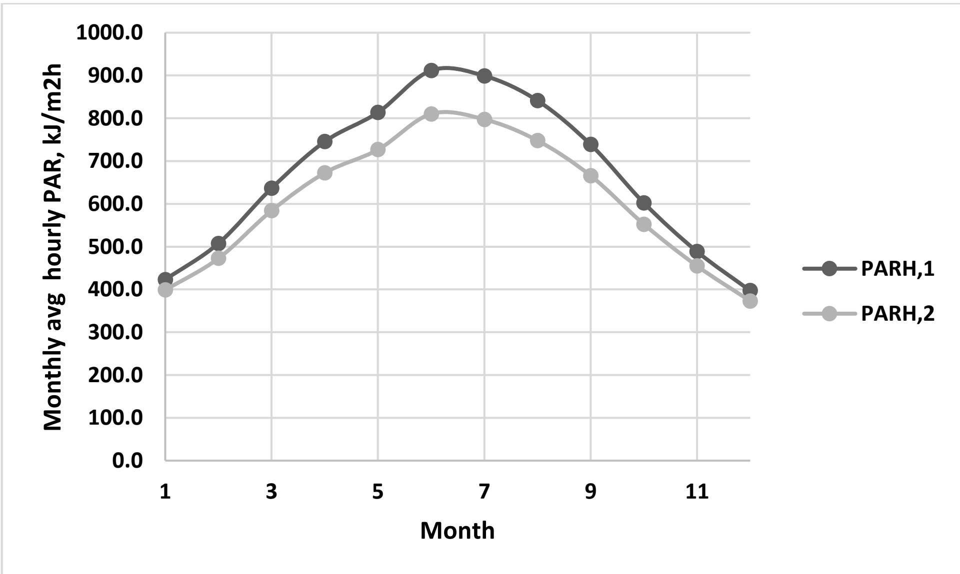


**Fig 3**: Monthly average hourly photosynthetically active radiation, $\overline{PAR}_{H,j}$ incident on a horizontal surface at New Delhi computed using two different relations for $I_o$.

Theaverage value of instantaneous diffuse PAR varies between 24- 125W/m$^2$ for the entire year as shown in fig 2. However, the monthly average hourly diffuse PAR varies from 107-465kJ/m$^2$h and 100-413 kJ/m$^2$h respectively when $I_o$ is computed using eq 5 and 6 as shown in fig 4.

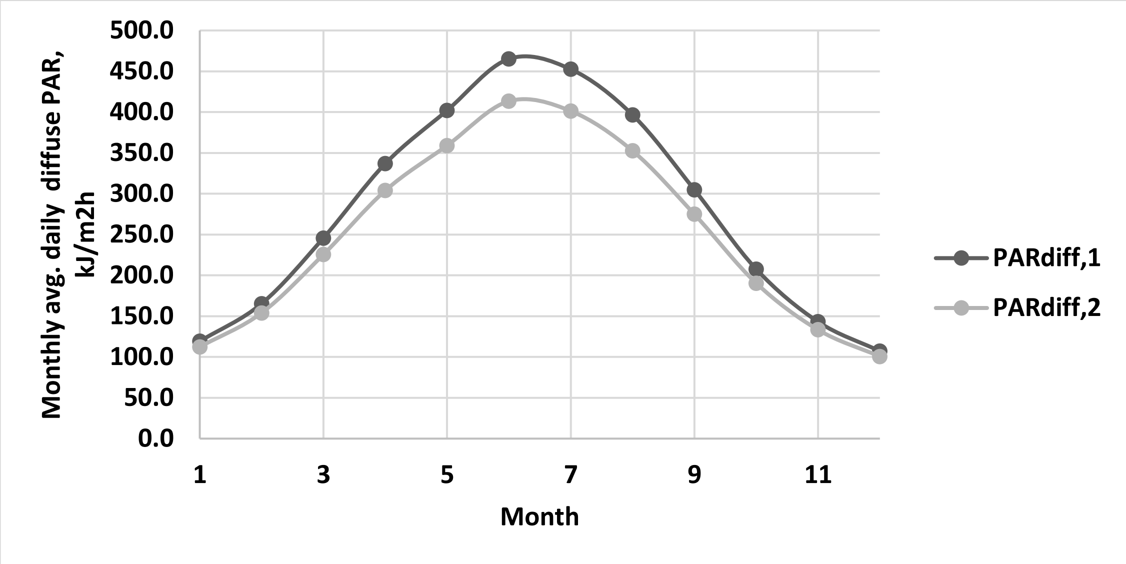


**Fig 4**: Monthly average hourly diffuse photosynthetically active radiation, $\overline{PAR}_D$ incident on a horizontal surface at New Delhi computed using two different relations for $I_o$.

It is observed that on an average 47% of interrow spacings between the panels are mostly shaded during the year. However, the shading in the interrow spacings increases during the winter months and hence during this time the plants which are grown in this region will receive majorly $PAR_{diffuse}$. Only during the summer months that 20-30% of the space remains under the shadow and hence plants recives both direct and diffuse component of PAR.

The results obtained is compared with the observed values reported by Ghayas et al. (2022) for the range of the peak PAR values for the winter, summer, monsoon and post monsoon season in New Delhi and presented in Table 2

**Tab 2: Comparison of results for peak value of PAR**

| | Winter | | Summer | | Monsoon | | Post monsoon | |
|---|---|---|---|---|---|---|---|---|
| | Proposed | Ghayas et al. 2022 | Proposed | Ghayas et al. 2022 | Proposed | Ghayas et al. 2022 | Proposed | Ghayas et al. 2022 |
| Min of peak PAR, W/m$^2$ | 229.2 | 101.8 | 448.5 | 311.5 | 324.8 | 378.4 | 233.7 | 214.3 |
| Max of peak PAR, W/m$^2$ | 378.3 | 353.5 | 463 | 515.7 | 459.3 | 560.5 | 272.9 | 477.5 |
| **%error, min of peak PAR** | | -1.25 | | -0.44 | | 0.14 | | -0.09 |
| **%error, max of peak PAR** | | -0.07 | | 0.10 | | 0.18 | | 0.43 |

The percentage error for the minimun value for the peak PAR varies between 9-125% showing a considereable agreement of the result for the monsoon and post monsoom months but there is a positive bias seen in the PAR values for the summer and winter months using the proposed model. Whereas, the percentage error for the maximum peak PAR values ranges between 7-43% having the least error during the winter and maximum error during the post monsoon season.

## Conclusions

The proposed model can be utilised to estimate the photosythetcally active solar radiation under a solar photovoltaic power plant for any location. The information regarding the available PAR can be utilised to select the variety of plant that can be grown under the solar PV powerplant. The proposed model shows considerable agreement with the observed maxima of the peak values of PAR during the summer, winter and monsoon season. The model is simple and utilizes only the location, date and time of the day for computing the PAR values.

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