95. Clear Sky Models Applied for PV Production Assessment from Solar Irradiance

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Abstract

PV is one of the best ever emergent renewable energy technologies and it is predictable that it will play a key role in the future worldwide electricity generation mix. This paper addresses the estimation of expected electrical energy produced by Photo Voltaic (PV) panels resulting from solar irradiation as a function of time. The Solar Insolation reaching the earth's surface can be estimated using clear sky models. In order to estimate the Electrical output of the Photovoltaic panels, the knowledge of Global Horizontal Irradiance (GHI) incident upon the surface of earth is a necessity. The Global Horizontal Irradiance is the sum of Beam and Diffuse radiation incident upon the PV panel. For this purpose, we apply KASTEN, DISC, KLUCHER model and PEREZ algorithm. KASTEN model is used estimate GHI on horizontal surface. Direct Isolation Simulation Code (DISC) model is used to break up the computed GHI into Direct Normal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI) components which is used to compute irradiation on tilted surface. The beam irradiance on tilted surface is estimated using PEREZ algorithm. The diffuse irradiance on tilted surface is estimated using KLUCHER model. The findings of this study may be used for development of a software tool that uses the above mentioned models to estimate the Electrical power output of the PV panel at any fixed tilt and azimuth on a clear day at given latitude and longitude.

Keywords: *Photovoltaic (PV); Irradiance; Clear sky models; Global horizontal Irradiance; DNI;*

1. Introduction

The economic and social development of any country is generally assessed by the energy consumption per capita. In developed countries the amount of energy required to maintain standard of living and comfort is 10kW per person in USA, about 5kW per person in Europe and about 0.5kW per person in developing countries. With the increase in population and rapid industrialization, the demand of Electrical Energy is also increasing rapidly. The electrical energy generated through conventional sources i.e. Hydro, Oil, Coal and Natural gas is therefore not sufficient to fulfill the energy demand. It is pertinent to mention that more than half of the electrical energy generated throughout the world is utilized by approximately one third of the world's population living in developed countries. As such the share left for the underdeveloped countries is much small. Keeping in view the energy needs of the future, alternate resources of electrical energy need to be explored. Out of presently available alternate energy resources, solar energy now emerges as a clean and safe source of energy. The direct method of producing electrical power from solar energy is from solar irradiation. The solar irradiation available above the earth's atmosphere is much higher than that received at the earth's surface. The loss being inherent to the presence of different atmospheric gases, clouds, pollution (including aerosols) and other environmental effects. The solar insolation incident upon the earth's surface can produce $1kW/m^2$ if converted efficiently [1]. In order to extract optimum electrical energy from the solar power through PV panels, the amount of *solar insolation* incident upon a specific area and the duration of sunshine are important. One way to get information about the solar irradiation is through sensors mounted on specific location and get data about the required parameters but this is a costly method. Another way is to use clear sky models to approximate the required parameters in order to estimate the expected electrical energy produced by photovoltaic panel resulting from solar irradiation as a function of time. Ground irradiance measurement sites are not always available, requiring the use of models to estimate irradiance in lieu of measurements [2]. There are three categories of clear sky models for determine the irradiance on a clear day.

Very simple models use only geometric calculation to estimate GHI. Simple models include some parameters in addition to geometric calculation such as air pressure, aerosol content, relative humidity, Rayleigh scattering and temperature. Complex models consider various measurable atmospheric parameters like ozone and perceptible water [3-4]. The focus of this paper is to develop a software by implementing clear sky models for estimation of solar irradiance on a tilted PV panel and the amount of electrical power produced by the panel as a function of time. The software uses a MATLAB tool GUI that has been established for inputting the parameters which are essential for computing power for specific day and corresponding results have been shown in the form of graphs. A 250 Watt PV panel is used for getting information about the power as reference. By getting the information about the power for a single day, we can estimate the amount of energy produced that day. Once energy for a single day is known, the amount of energy will be estimated for the whole month and then for the whole year. We also estimate the approximate tilt angle of the panel for getting maximum energy from the panel keeping the surface Azimuth fix.

The rest of the paper is organized as follows Section 2 describes the basic parameters which have been studied so far. Section 3 describes the models which are implemented for estimation of PV output power. Section 4 describes the tools through which we are able to compute the output electrical energy of the system. Section 5 shows the output result in the form of graphs and tables. Section VI gives the conclusion and future work of the research

2. Parameters in PV Output Estimation

The revolution of earth around the sun traverses an elliptical path with the sun at one of the foci. As we know the main source of energy for PV power production is sun. These radiations travel through space and strikes on the outer layer of the earth's atmosphere. The energy received surface of atmosphere at normal incidence per unit area at the sun –earth mean distance is termed as *Solar Constant* E_{sc} whose value is 1367wm^{-2} [5].The declination of sun δ is basically the angle between the line drawn from the center of the earth and equator to the center of the sun. The diurnal change in amount of radiation is due to rotation of earth around its own axis.δ = 0 for autumnal and vernal equinox. δ=maximum(23.45°) in summer solistics,δ = minimum (-23.45°) in winter solistics [6].

Simple representation of declination angle given in ASCE [7]:

$$\delta = sin^{-1}(sin(23.45°)sin(360/365(d-81))) \quad (1)$$

Where d is day of year. d =1 for 1st January.

Solar zenith angle is the angle between line drawn from the sun to earth's surface and the normal. It is the angle between the normal and the sun. This angle gives a measure of the height of sun with respect to horizon [8]. Calculation of zenith angle is given by (Duffie 2006) as:

$$Cos\ (\theta_z) = Cos\ (\lambda).Cos(\delta).Cos\ (\omega)\ Sin\ (\lambda).Sin\ (\delta) \quad (2)$$

λ= latitude of location , δ= Declination angle ,ω = Hour angle.

Hour angle is the angular distance between the object and meridian, measured in hours. It is the angular displacement between the position of sun caused by rotation of earth and local meridian. It is the angle traced by sun in 1 hour with reference to 12 noon. One hour is represented by fifteen degrees [9].

$$\omega[deg] = (Solar\ Time[h] - 12) \times 15 \quad (3)$$

The azimuth is the angle along the horizon, with zero *degrees* corresponding to North and increases in clockwise fashion. Thus 90 *degrees* is East, 180 *degrees* is South and 270 *degrees* is West [10].

$$\text{Azimuth}=cos^{-1}(\frac{\sin(\delta).\cos(\lambda)-\cos(\delta).\sin(\lambda).\cos(w)}{\cos(90-\theta_z)} \quad (4)$$

The angle which an incident sun rays makes with a perpendicular to the surface at the point of incidence IS called angle of incidence The incident power on PV module also depends on the angle between the sun and PV module. The solar radiation intensity is a function of angle of incidence [11].

$$\alpha_{fixed} = cos^{-1}[\sin(\theta_{sun}).\cos(\gamma - \gamma_{sun}).\sin(\beta) + \cos(\theta_{sun}).\cos(\beta)] \quad (5)$$

where
θ_{sun} = Solar zenith angle
γ_{sun} = Solar azimuth
γ = Surface azimuth
β = Surface tilt
Air mass represents the optical thickness of atmosphere through which the solar radiation must pass before reaching the earth's surface.

$$AM = \frac{1}{\cos(\theta_z)} \quad (6)$$

A value of 1 of air mass present when zenith angle is zero (sun is absolute overhead). Any variation of zenith angle from zero value increases AM value [12]. Extra-terrestrial radiation incident on a surface which is normal to incoming solar radiation, E_{ext}

$$E_{ext} = E_{sc}.(1 + 0.033.\cos(\frac{360.n}{365})) \quad (7)$$

E_{ext} = Extraterrestrial solar irradiance.
E_{sc} = Solar constant (1367 Wm^{-2})
n is nth Julian day of given year.
For utilizing solar irradiance models, the concept of extraterrestrial radiation on horizontal surface must be understood. Consider there is flat plate surface adjustment outside the atmosphere of earth. When this flat plate faces the sun, the solar irradiance E_{ext} will be maximum. If the plate surface is not normal to sun, the solar irradiance reduces by cosine of the angle between central ray of the sun and normal to flat plate surface [7]. The extraterrestrial solar irradiance on horizontal surfaces which is basically parallel to ground is computed as:

$$E_{h\_ext} = E_{ext}.\cos(\theta_z) \quad (8)$$

3. Different Models for PV Output Estimation

There is variety of models which we can after deep study be selected for our simulation.

3.1 KASTEN Model

One of the simple models which we are used for calculating GHI is KASTEN model [13] that caters different atmospheric parameters like elevation and atmospheric turbidity. The input parameters of this model are Elevation (h), Air mass (AM) and Linke turbidity (TL).

$$\mathrm{GHI} = 0.84 \times \mathrm{E_{ext}} \times \cos(\mathrm{z}) \times \exp(-0.027 \times \mathrm{AM} \times (\mathrm{f_{h1}} + \mathrm{f_{h2}}(\mathrm{TL} - 1))) \quad (9)$$

$$\text{where } \mathrm{f_{h1}} = \exp\left(-\frac{\mathrm{h}}{8000}\right) \text{ and } \mathrm{f_{h2}} = \exp\left(-\frac{\mathrm{h}}{1250}\right)$$

f_{h1} and f_{h2} are coefficients which are used in KASTEN model relating the altitude of station/location with the altitude of atmospheric interactions (Aerosols and Rayleigh scattering).Now task is to separate beam and diffuse radiation from GHI which have already get from KASTEN model

3.2 DISC model to determine DNI

Disc model is considered as Quasi physical model as developed by scientist of solar energy research institute for transforming GHI values to DNI. In 1987 Maxwell concluded that DNI can be calculated easily if we are giving GHI and zenith angle as input. DISC model is basically developed in sequential way. Its level of simplicity changes in every stage. Maxwell observed some climatically and seasonal variations in relationship between K_t and K_n which is direct beam transmittance and given as:

$$K_n = \frac{E_n}{E_{ext}} \tag{10}$$

K_{nc} and K_{tc} represent maximum clear sky value. ΔK_t and ΔK_n are basically the departure of transmittance value from its respective maximum values K_{nc} and K_{tc}. Deviation from maximum values is due to arbitrary values of air mass, cloud cover and perceptible water vapor. Relationship of ΔK_t and ΔK_n is given as:

$$\Delta K_n = K_{nc} - K_n \tag{11}$$

and

$$\Delta K_t = K_{tc} - K_t \tag{12}$$

For establishing maximum clear sky direct transmittance value, Bird clear sky model is used which is derived in 1981 and given as:

$$K_{nc} = 0.866 - 0.122\ \text{AM} + 0.0121\ \text{AM}^2 + 0.000653\ \text{AM}^3 + 0.000014\ \text{AM}^4 \tag{13}$$

Next the exponential relationship between ΔK_n and AM is used to derive the ΔK_n which was derived from least square regression analysis and given as:

$$\Delta K_n = a + b.\exp(c.AM) \tag{14}$$

The clearness value K_t strongly depends on CC effects. The dependence of this introduces the coefficients a , b and c as mentioned above. These values are computable from polynomial functions and expressed in terms of K_t and given as:

If $K_t \leq 0.60$ (cloudy conditions)

$$a = 0.512 - 1.56\,.K_t + 2.286\ K_t{}^2 - 2.222.K_t{}^3$$
$$b = 0.370 + 0.962\,.K_t$$
$$c = -0.280 + 0.932.K_t - 2.048.K_t{}^2$$

If $K_t \geq 0.60$ (mostly clear conditions)

$$a = -5.743 + 21.77.K_t - 27.49.K_t{}^2 + 11.56.K_t{}^3 \qquad b = 41.40 - 118.5.K_t + 66.05.K_t{}^2 + 31.90.K_t{}^3$$
$$c = -47.01 + 184.2.K_t - 222.0.K_t{}^2 + 73.81.K_t{}^3$$

So direct beam transmittance value K_n can be computed easily if we compute maximum beam transmittance value K_{nc} and departure ΔK_n from maximum value and given by simple relationship.

$$K_n = K_{nc} - \Delta K_n \tag{15}$$

By knowing K_n, direct normal irradiance can be computed as:

$$E_n = E_{ext}\,.\,K_n \tag{16}$$

Once direct normal irradiance (E_n) is known, the separation of global horizontal irradiance E_g in to horizontal beam and horizontal diffuse can be computed as:

$$E_g = E_{bh} + E_{dh} \tag{17}$$

3.3 Beam Radiation Model

Beam radiation can be determined by the relation between *direct normal irradiance* E_n and angle of incidence α . Beam radiation on a tilted surface is a simple function of angle of incidence between line drawn normal to surface and incoming *direct normal irradiance*. It is expressed as:

$$I_b = E_n.\cos(\alpha) \tag{18}$$

where α is angle of incidence.

3.4 Diffuse Radiation Model

The technique used for determine the ratio of diffuse solar irradiance on tilted surface to that of flat horizontal surface can be categorized in to *anisotropic* and *isotropic* models. The isotropic models suppose that intensity of diffuse radiation in sky is steady or uniformly distributed over the sky dome, so diffuse irradiance incident on panel which is at some tilt depends on part of sky dome seen by it. Whereas in *anisotropic* models there are three *diffuse* subcomponents which are used to estimate the pattern of *anisotropic diffuse radiation*. These are:

- Circumsolar radiation
- Horizon Brightening
- Isotropic diffuse radiation

Hay and Davies [14] have calculated a model which accounts for both isotropic and circumsolar diffuse irradiances. They introduce an anisotropy index A_l which is the ratio of hourly beam radiation on horizontal surface and hourly *extra-terrestrial radiation.*

$$A_l = \frac{I_b}{I_o} \tag{19}$$

This index defines a part which is considered as a circumsolar while remaining part is considered as *isotropic diffuse radiation*. This circumsolar diffuse is reckoned on tilted surface in the same way as beam radiation.

$$I_{T,cir} = I_d A_l R_b \tag{20}$$

I_d = Hourly diffuse horizontal radiation
R_b= beam radiation geometric factor. It is the ratio of beam radiation on tilted surface to beam radiation on horizontal surface.
The remaining diffuse radiation is considered as isotropic diffuse radiation.

$$I_{T,iso} = I_d(1 - A_l)(\frac{1+\cos\beta}{2}) \tag{21}$$

The overall diffuse radiation on tilted surface is:

$$I_{d,T} = I_d\left[(1 - A_l)\left(\frac{1+\cos\beta}{2}\right) + A_l R_b\right] \tag{22}$$

The *Hay and Davies Model* don't consider horizon brightening. So *Temps and Coulson* [15] approximated the effect of horizon brightening by adding a correlation factor $[1 + sin^3(\beta/2)]$ to isotropic diffuse radiation. Further *Klucher Model* [16] added some correction factor F=$\sqrt{I_b/I}$ in *Temps and Coulson Model*.so horizon brightening effects can be compensated by adding factor $[1 + Fsin^3(\beta/2)]$ in diffuse radiation. So the overall anisotropic model which cover isotropic diffuse, circumsolar diffuse and horizon brightening diffuse radiation can be estimated as:

$$I_{d,T} = I_d\left[(1 - A_l)\left(\frac{1+\cos\beta}{2}\right) \times 1 + Fsin^3(\beta/2) + A_l R_b\right] \tag{23}$$

Where I is total horizontal *radiation.*

3.5 Ground Reflected Radiation or Albedo Model

Nkemdirim's Model [17-18]. In this model, ground reflected radiation depends on height of sun h:

$$\rho = \rho_o.\exp(b.(90 - h)) \tag{24}$$

Where "h" is in degrees, "b" is a positive coefficient. The coefficients b and $\rho_o$are site dependent. ρ applies to G_h as usual. If radiations after ground reflection are isotropic, then its part on inclined plane is:

$$R_i = \rho . G_h . \left(\frac{1}{2}\right)(1 - \cos(s)) \quad (25)$$

Where "s" is a tilt of panel from the horizontal plane.

3.6 Perez Algorithm

Plane of array beam, ground reflected and diffuse components are integrated using *Perez algorithm 1990* [19]. The I_b beam component is cosine of incidence angle multiplied with beam normal input E_n. The $I_{d,sky}$ is total sky diffuse component on horizontal surface. The ground reflected radiation is considered as isotropic diffuse with a viewed factor determined from ground w.r.t tilted surface. The POA incident on PV panel is a sum of three components.

$$I_{poa} = I_b + I_{d,sky} + I_{d,ground} \quad (26)$$

The ground reflected component $I_{d,ground}$ has a default value as 0.2.whereas ground reflectance by snow is about 0.6.
As we know irradiance POA on module**.** The incident POA is reduced by giving incidence angle (α), beam normal radiation E_n and five polynomials for PV module.

$$f = b_o + b_1\alpha + b_2\alpha^2 + b_3\alpha^3 + b_4\alpha^4 + b_5\alpha^5 \quad (27)$$

$$I_{tr} = I_{poa} - (1 - f). E_n . \cos(\alpha) \quad (28)$$

Where b_i are module cover polynomial coefficients.

3.7 Model of PV Module for computing power

The PV Watts module has been used for computing power which is an adaptation of PVFORM version 3.3 models [20-21]. DC power from an array can be computed by giving rated panel powerP_{dc0}, cell temperature T_{cell} and POA irradianceI_{tr}. The efficiency of panel is decreased by increasing rate of temperature rise.

$$P_{dc} = \frac{I_{tr}}{1000} . P_{dc0}(1 + \gamma(T_{cell} - T_{ref})) \quad (29)$$

$$I_{tr} > 125\ wm^{-2}$$

Where
γ =temperature coefficient and fixed at -0.5% / $°C$ and considered for silicon crystalline PV module.
T_{ref} = 25 $°C$
and the effect of performance of PV module on low light conditions at fixed tilt cab ne modified as:

$$P_{dc} = \frac{0.008 . I_{tr}{}^2}{1000} . P_{dc0}(1 + \gamma(T_{cell} - T_{ref})) \quad (30)$$

$$I_{tr} < 125\ wm^{-2}$$

4. Tools and Implementation

The software tool for implementation the whole process is MATLAB. A guide user interface (GUI) has been established for inputting the parameters which are essential for computing power and corresponding results have been shown in the form of graphs. A sample GUI is shown in the Fig 1:

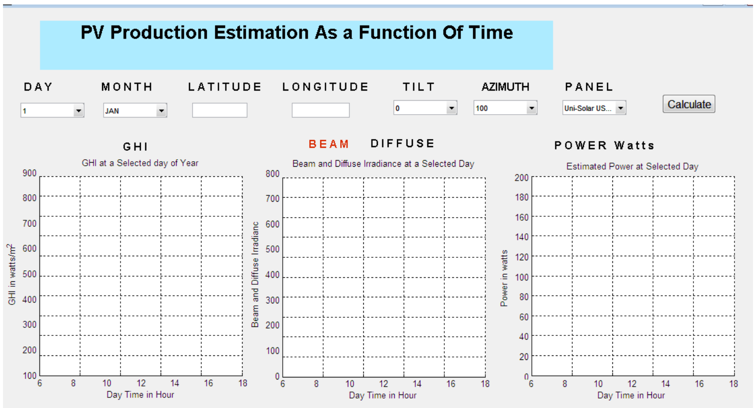

Fig. 1. Sample of GUI

- Any day of the month can be selected from popup menu of day.
- Any month of the year can be selected from popup menu of month.
- Latitude must be given in the textbox of LATITUDE.
- Longitude must be given in the textbox of LONGITUDE.
- Tilt of the panel from the ground can be selected from popup menu of tilt.
- Panel Azimuth (From North) can be selected from popup menu of Azimuth
- Calculate button estimate the resulting power output at a given day.

There are 3 different graphs shown in the figure.

- The first one estimates GHI on the surface of earth at given day.
- The second one estimates the Beam and Diffuse irradiance on the surface of earth at given day.
- The third one estimates the power output of 250Watt panel during the whole day when there is a sun light.

5. Simulation Results

The estimating power for summer solstice and winter solstice has been shown with only variation in tilt angle while surface azimuth is fixed at 180°.

PV output in Summer Solstice
Tilt angle is 5° , Surface Azimuth is 180°

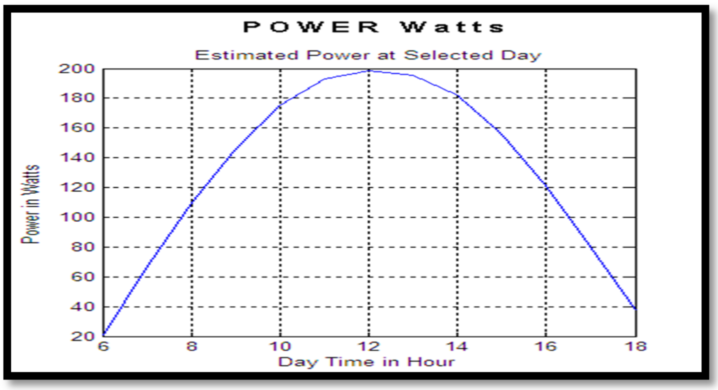

Fig. 2 Power output at 21 June, Tilt angle 5°, Surface Azimuth 180°, Latitude 33.7° and Longitude 73.1°

Fig 2: shows that there is a graph of power output from 250w solar panel. X-axis shows time in hours while Y-axis shows expected output power in watts on respective hour of the day. This graph approximates the power using above mentioned clear sky models. Graph shows that there is 110w at 8AM, there is a peak power of almost 200 at 12PM and there is almost 40w at 6PM on 21 June which is almost 20w. By giving inputs to GUI as shows above we can approximate power and then we can easily compute energy on a given day, on a given month and on a given year.

Tilt angle is 70° , Surface Azimuth is 180°

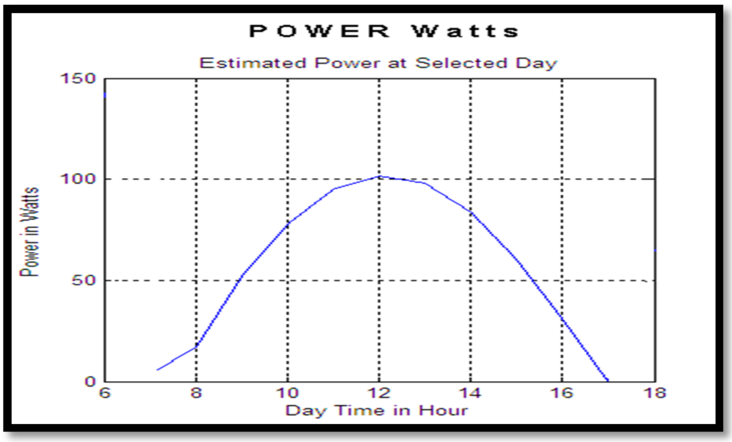

Fig. 3. Power output at 21 June, Tilt angle 70°, Surface Azimuth 180°°, Latitude 33.7° and Longitude 73.1°

Fig. 3: shows that there is a graph of power output from 250w solar panel. X-axis shows time in hours while Y-axis shows expected output power in watts on respective hour of the day. This graph approximates the power using above mentioned clear sky models. Graph shows that there is 20w at 8AM, there is a peak power of almost 100w at 12PM and there is almost 30w at 6PM on 21 June which is almost 20w. By giving inputs to GUI as shows above we can approximate power and then we can easily compute energy on a given day, on a given month and on a given year.

5.2 PV output in Winter solstice

5.2.1. Tilt angle is 5° , Surface Azimuth is 180°

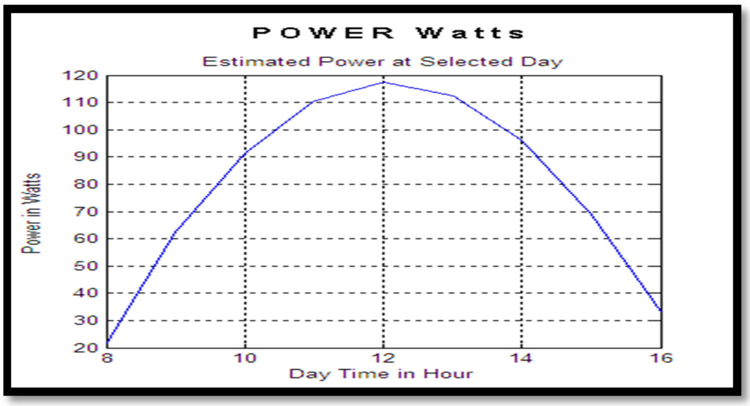

Fig. 4. Power output at 21 Dec, Tilt angle 5°, Surface Azimuth 180°°, Latitude 33.7° and Longitude 73.1°

Fig. 4: shows that there is a graph of power output from 250w solar panel. X-axis shows time in hours while Y-axis shows expected output power in watts on respective hour of the day. This graph approximates the power using above mentioned clear sky models. Graph shows that there is 25w at 8AM, there is a peak power of almost 115w at 12PM and there is almost 35w at 4PM on 21 June which is almost 20w. By giving inputs to GUI as shows above we can approximate power and then we can easily compute energy on a given day, on a given month and on a given year.