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# Solar irradiance and optimum tilt angle of photovoltaic module in Tanjung Morawa, North Sumatera, Indonesia

**M. Irwanto**

Department of Electrical Engineering, Medan Institute of Technology, Medan, Indonesia.

**Abstract**

The performance of a photovoltaic (PV) module is influenced by its tilt angle with the horizontal, due to the tilt angle change the amount of climate condition (solar irradiance and temperature) reaching the surface of the PV module. The optimum tilt angle is needed to get the maximum solar irradiance and the minimum temperature along day reaching the surface of the PV module. This paper presents a calculation of the tilt angles and the solar irradiance on PV module in Tanjung Morawa, North Sumatera, Indonesia. A mathematical modeling is used to calculate the tilt angles and the solar irradiance, which depend on latitude and day number. The optimum tilt angle of PV module is determined by searching a yearly maximum total and average solar irradiance. The tilt angles of PV module in Medan, are -19.92$^0$ to 26.08$^0$. The positive, zero and negative tilt angles indicate that the PV module is inclined to face south, on horizontal surface and north, respectively. The yearly minimum, maximum and average solar irradiance are 988.5 W/m$^2$ and 1123 W/m$^2$ and 1061 W/m$^2$, respectively. For Tanjung Morawa, North Sumatera, Indonesia (has latitude 3.53 $^0$ N) is recommended that the optimum tilt angle of the PV module from the horizontal be put equal to 5.08$^0$ (an angle of the latitude of the location +1.55$^0$).

**Keywords:** Solar irradiance, temperature, tilt angle, photovoltaic.

## 1. Introduction

The performance of a photovoltaic (PV) is highly influenced by its orientation and its tilt angle with the horizontal, due to the fact that both the orientation and tilt angle change the amount of solar radiation reaching the surface of the PV module, presented by Chang [1]. The tilt angle of the fixed-structure PV module should be carefully evaluated for different places and periods of time to obtain the maximum overall output electrical energy. A mathematical model was used by Kacira [2] to estimate the global solar irradiance on the tilt PV surface, and to determine optimum tilt angles for PV module, the optimum tilt angle were determine by searching for the value of angle for which the global irradiance on the PV module surface was maximum. Empirical correlation for estimating the solar irradiance incident on horizontal surface have been proposed by El-Sebaii [3], the result shown that in Jeddah (Saudi Arabia), the solar irradiance have to be tilted to face south with a tilt angle equals the latitude of the place in order to achieve the best performance all year round.

The optimum tilt angles of the PV module at any latitude, for any surface azimuth angles and on a day or a month of a year, have to be determined for design purpose. Definite value is rarely given by researchers for optimum tilt angles. The suggested optimum tilt by Mahmoud [4] is latitude angle $\pm 15^0$, (latitude angle + 15$^0$) $\pm 15^0$ by Masters [5] and latitude angle $\pm 15^0$ by Yorukoglu [6]. The optimal PV tilt angle and orientation depend on the local climate, the load consumption temporal profile and latitude. Research result of Kuin [7] shown that using PV mounting structure of adjustable tilt angle can be obtained PV performance improvement of 5.6%.

This paper presents a calculation of the tilt angle and the solar irradiance on PV module in Medan, Indonesia. Method of Pandey [8] is used to calculate the tilt angle and the solar irradiance, which depend on latitude and day number. The tilt angle and solar irradiance change every day in a year and analyzed. The monthly average solar irradiance are shown and analyzed in this paper.

## 2 Methodology

### 2.1 Latitude of Tanjung Morawa

Tanjung Morawa is situated in Deli Serdang regency, North Sumatra, Indonesia. It has latitude of 3.53$^0$ N and land area of 131,75 km² as shown in Figure 1.


**Fig 1:** Map of Tanjung Morawa has latitude of 3.53$^0$ N and land area of 131,75 km² [9]

### 2.2 Solar Irradiance

The electricity power generated by PV systems is directly related to the solar energy received by the PV module, while the PV module can be placed at any orientations and any tilt angles, but most local observatories only provide solar irradiance data on a horizontal surface. Thus, an estimation of the solar irradiance on a tilt surfaces is calculated by adding the beam, diffuse, and reflected solar irradiance components on the tilt surface together by Pandey [8], as in Figure 2.

The total solar irradiance on tilt surface is given by:

$$I_{tt} = I_{bt} + I_{dt} + I_{rt} \tag{1}$$

where $I_{tt}$ is the total solar irradiance on the tilt surface, $W/m^2$; $I_{bt}$ is the total beam solar irradiance absorbed by the tilt surface, $W/m^2$; $I_{dt}$ is the total diffuse solar irradiance absorbed by the tilt surface, $W/m^2$; and $I_{rt}$ is the total reflected solar irradiance absorbed by the tilt surface, $W/m^2$.

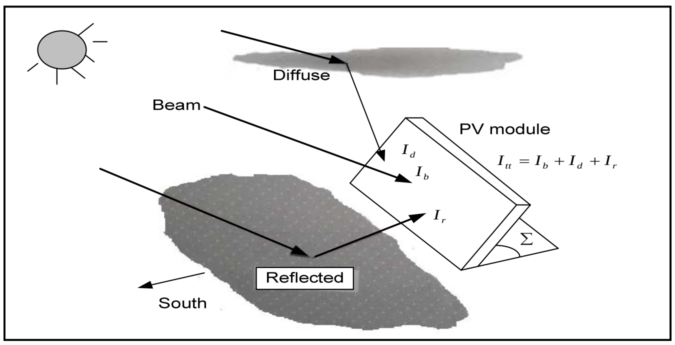


**Fig 2:** Total solar irradiance of tilt surface of PV module

#### 2.2.1 Beam Solar Irradiance

The translation of direct-beam irradiance $I_b$ (normal to the rays) into beam into beam irradiance striking a PV module face $I_{bt}$ is a simple function of the angle of incidence $\theta$ between a line drawn normal to the PV module face and the incoming beam irradiance. It is given by

$$I_{bt} = I_b \cos\theta \tag{2}$$

where $I_b$ is the beam portion of the radiation reaching the earth's surface (normal to the rays), is given by

$$I_b = Ae^{-km} \tag{3}$$

where $A$ is an "apparent" extraterrestrial flux, and $k$ is a dimensionless factor called the optical depth, given by

$$A = 1160 + 75\sin\left[\frac{360}{365}(n - 275)\right] \tag{4}$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right]$$

(5)

The air mass ratio $m$ is given by

$$m = \frac{1}{\sin\beta} \tag{6}$$

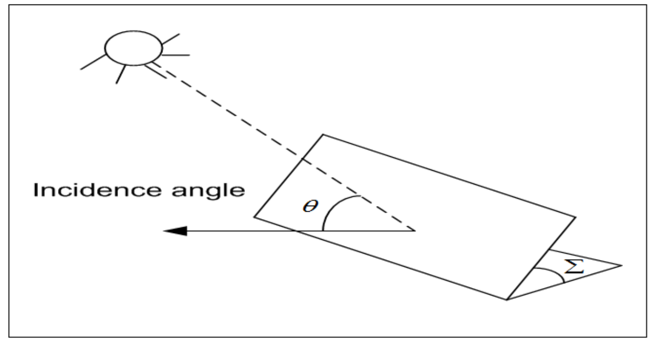


**Fig 3:** The incidence angle $\theta$ between a normal to the PV module face and the incoming solar beam irradiance

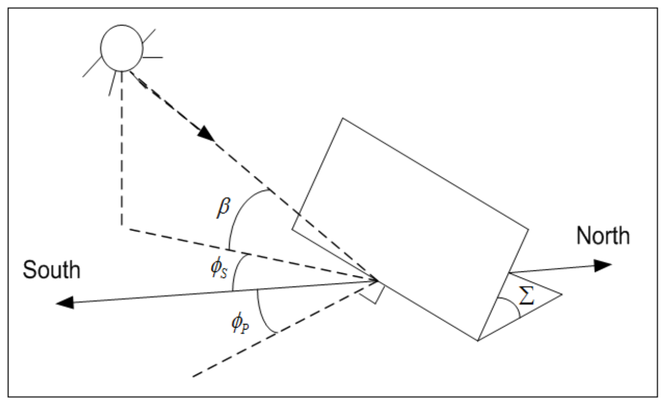


**Fig 4:** Illustrating the PV azimuth angle $\phi_P$ and tilt angle $\Sigma$ along with the solar azimuth angle $\phi_S$ and altitude angle $\beta$. Azimuth angles are positive in the southeast direction and are negative in the southwest

The angle of incidence $\theta$ will be a function of the photovoltaic orientation and the altitude and azimuth angles of the sun at any particular time. Figure 5 introduces these importance angles. The photovoltaic is tipped up at angle $\Sigma$ and faces in a direction described by its azimuth angle $\phi_P$ (measured relative to due south, with positive value in the southeast and negative value in the southwest). The incidence angle is given by

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_P)\sin\Sigma + \sin\beta\cos\Sigma \tag{7}$$

The solar azimuth angle $\phi_S$ is given by Pandey [8]

$$\sin\phi_S = \frac{\cos\delta\sin H}{\cos\beta} \tag{8}$$

where $H$ is hour angle ( the number of degrees that the earth must rotate before the sun will be directly over local meridian or line of longitude), is given by Castaner [10]

$$H = \cos^{-1}(-\tan L \tan\delta) \quad (9)$$

### 2.2.2 Diffuse Solar Irradiance

The simplest models of diffuse irradiation assume it arrives at a site with equal intensity from all direction; that is, the sky is considered to be isotropic. Obviously, on hazy or overcast days the sky is considerably brighter in the vicinity of the sun, and measurements show a similar phenomenon on clear days as well, but these complications are often ignored. The following expression for diffuse irradiance on the photovoltaic module.

$$I_{dt} = CI_b\left(\frac{1+\cos\Sigma}{2}\right) \quad (10)$$

where $C$ is a sky diffuse factor and a convenient approximation is a follows :

$$C = 0.095 + 0.04\sin\left[\frac{360}{365}(n-100)\right] \quad (11)$$

### 2.2.3 Reflected Solar Irradiance

The final component of irradiance striking a photovoltaic module results from radiation that is reflected by surfaces in front of the module. The simplest model assumes a large horizontal area in front of the module, with a reflectance $\rho$ that is diffuse, and it bounce the reflected irradiance in equal intensity in all direction. The solar reflected irradiance is given by

$$I_{rt} = \rho\, I_b(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right) \quad (12)$$

### 2.3 Tilt Angle of a PV Module

An altitude angle or solar angle $\beta_N$ is an angle between the sun and the local horizontal directly beneath the sun. The altitude angle of the sun at solar noon is shown in Figure. 5. From Figure. 5 can be written down the following relationship by inspection:

$$\beta_N = 90^0 - L + \delta \quad (13)$$

$$\Sigma = 90^0 - \beta_N \quad (14)$$

where $L$ is the latitude of the site, $\delta$ is solar declination (the angle formed between the plane of the equator and a line drawn from the centre of the sun to the centre of the earth) and $\Sigma$ is tilt angle of PV module. According to Pandey [8], the solar declination $\delta$ is given by:

$$\delta = 23.45\sin\left[\frac{360}{365}(n-81)\right] \quad (15)$$

where $n$ is day number, with January 1 as day 1 and December 31 being day number 365.

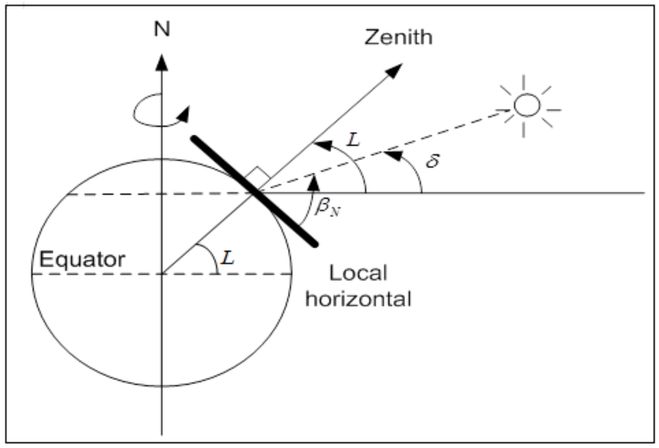


**Fig 5:** The altitude angle of the sun at solar noon

## 3 Results and Discussion

### 3.1 Tilt Angle of PV Module

The tilt angles of PV module were calculated using Equation (13) to (15) for a year. The first, the solar declination $\delta$ was calculated for 365 days in a year and latitude of Tanjung Morawa is $3.53^0$ N substituted in (13), finally the tilt angle $\Sigma$ could be calculated using Equation (14). The tilt angles of PV module in Tanjung Morawa are shown in Figure 6.

The tilt angles have positive degree which indicate that the PV module is inclined to face south, negative degree indicate that it inclined to face north and zero degree indicate that it on horizontal surface Daut [11].

Figure 6 shows that the tilt angles can be divided to three parts, exactly positive, zero and negative. From the 1st January to the 30th March, the tilt angles of PV module in Tanjung Morawa are positive ($26.54^0$ on the 1st January and $0.31^0$ on the 30th March) which indicate that the PV module inclined to face south. For the 31st March and the 13th September, the tilt angles are $0^0$ which indicate that the PV module on the horizontal surface. From the 1st April to the 12th September, the tilt angles are negative ($-0.09^0$ on the 1st April and $-0.26^0$ on the 12th September), maximum negative is $-19.92^0$ on the 21st June which indicate that the PV module inclined to face north. From the 13th September to the 31st December, the tilt angles are positive ($0.14^0$ on the 13th September and $26.98^0$ on the 31 December), maximum positive is $27.03^0$ on the 23rd December which indicate that the PV module inclined to face south.

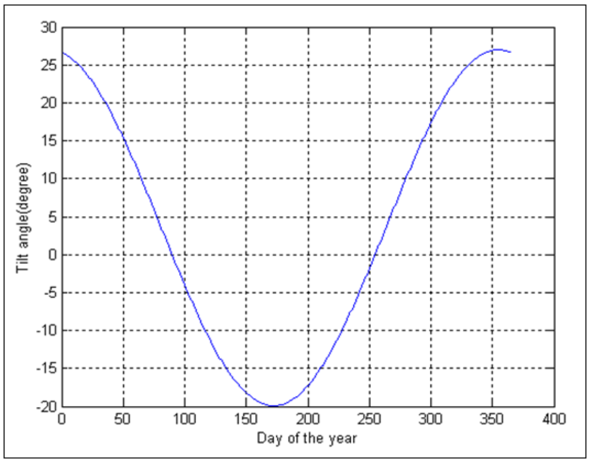


**Fig 6:** The tilt angle of PV module in Medan, Indonesia

### 3.2 Solar Irradiance on Tilt Angles of PV Module

The effect of tilt angles of PV module on solar irradiance is calculated using Equation (1) and (5) to (15) for a year. The solar irradiance on tilt angles of PV module are shown in Figure. 7.

Figure. 7 shows that the minimum, maximum and average solar irradiance are 988.5 W/m$^2$, 1123 W/m$^2$ and 1061 W/m$^2$ which indicate that the sky in Tanjung Morawa is clear and very high for a year and gives potential for PV power generation (Daut [11]).

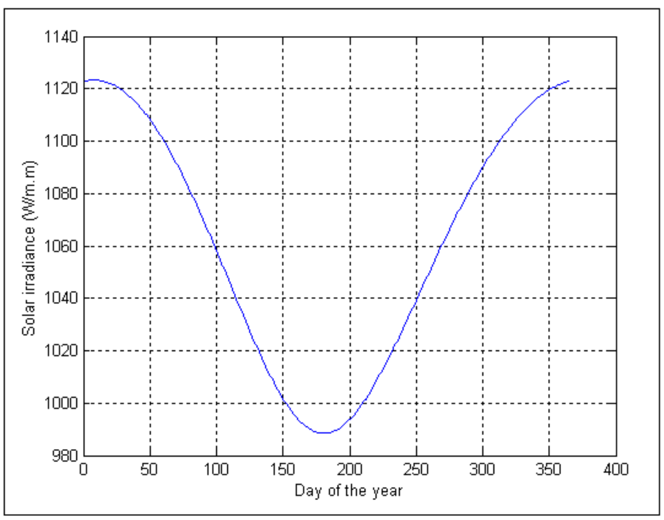


**Fig 7:** Solar irradiance on tilt angles of PV module

### 3.3 Optimum Tilt Angles of PV Module

Figure 8 indicates that the tilt angle has a very significant effect on the solar irradiance through the year. For the different tilt angle, the PV module has different solar irradiance through the year. For -19.92$^0$ of the PV module tilt angle, the minimum, maximum and average solar irradiance are 784.1 W/m$^2$, 1027 W/m$^2$ and 938.3 W/m$^2$, respectively. For horizontal PV module, the minimum, maximum and average solar irradiance are 934.7 W/m$^2$, 1081 W/m$^2$ and 1016 W/m$^2$, respectively. For 5.08 $^0$ of the PV module tilt angle, the minimum, maximum and average solar irradiance are 905.3W/m$^2$, 1092 W/m$^2$ and 1019 W/m$^2$, respectively. For 26.08$^0$ of the PV module tilt angle, the minimum, maximum and average solar irradiance are 724 W/m$^2$, 1123 W/m$^2$ and 960 W/m$^2$, respectively.

Every tilt angle (-19.92$^0$ to 26.08$^0$) of PV module in Medan is calculated to find the yearly total and average solar irradiance. The optimum tilt angle of PV module is determined by searching a yearly maximum total and average solar irradiance. This choice based on that under constant temperature if the solar irradiance increases, output power and efficiency of the PV module will increase (Castaner [10]). Figure 9 and 10 show the annual total and average solar irradiance on different tilt angle of PV module.

Figure 9 and 10 show that the annual maximum total and average solar irradiance are 372,000 W/m$^2$ and 1019 W/m$^2$ on 5.08$^0$ of the PV module tilt angle. Under this solar irradiance and constant temperature, the PV module will produce the highest output power and efficiency.

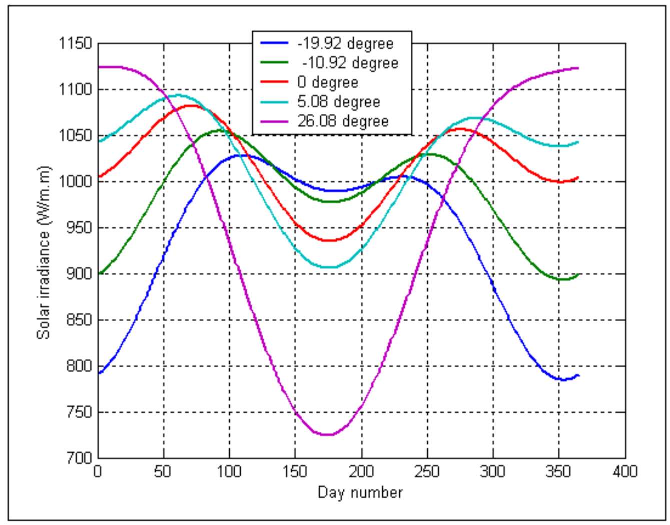


**Fig 8:** Solar irradiance through the year on different tilt angle of PV module

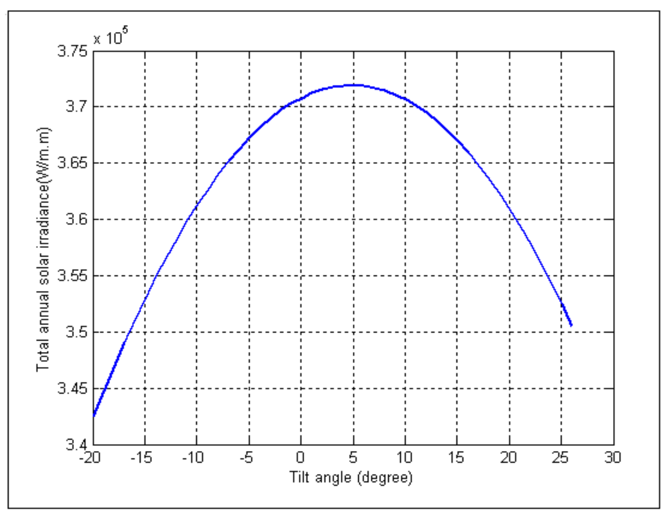


**Fig 9:** Annual total solar irradiance on different tilt angle of PV module

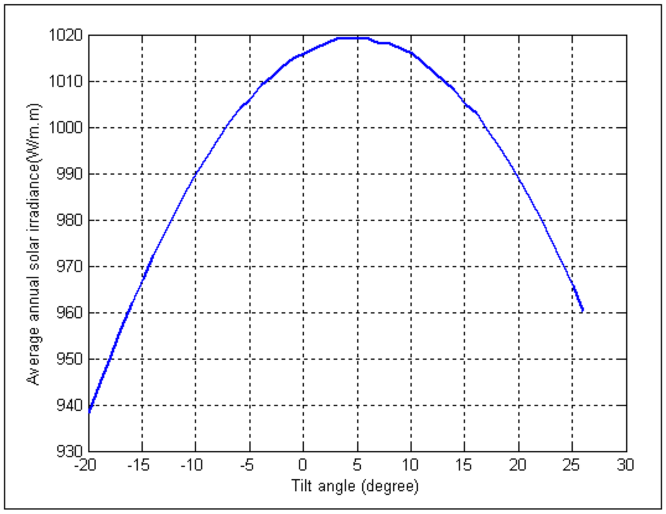


**Fig 10:** Annual average solar irradiance on different tilt angle of PV module

## 4. Conclusion

The tilt angles of PV module effect on the solar irradiance that fall on its surface. The tilt angles of PV module in Tanjung Morawa, North Sumatera, Indonesia are $-19.92^0$ to $26.08^0$. The positive, zero and negative tilt angles indicate that the PV module is inclined to face south, on horizontal surface and north, respectively.

The optimum tilt angle of PV module was determined by searching a yearly maximum total and average solar irradiance. The annual maximum total and average solar irradiance are 372,000 W/m$^2$ and 1019 W/m$^2$ on $5.08^0$ of the PV module tilt angle. Under this solar irradiance and constant temperature, the PV module will produce the highest output power and efficiency. For Tanjung Morawa, North Sumatera, Indonesia (has latitude $3.53^0$ N) is recommended that the optimum tilt angle of the PV module from the horizontal be put equal to $5.08^0$ (an angle of the latitude of the location $+1.55^0$).

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