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A Simplified Model for the Estimation of Solar Cell Efficiency Based on the Air Mass Effect

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Abstract

In this manuscript, a model for approximating the electrical power efficiency of the solar cells in relation with the air mass effect has been presented based on simple physical assumptions and in accordance with the solar radiation distribution. The model has been developed in correspondence with the air mass effect on the radiation intensity and wavelength and taking into account the energy gap effect of the silicon material.

Keywords

Air mass effect; Solar radiation; solar effeciences;PV moldel.

1. Introduction

In order to reduce dependence on fossil fuels renewable energy sources (such as solar radiation, wind, rain, tides, waves, and geothermal heat) have been studied intensively for many years [1]. As solar energy, one major source of renewable energies, depends on the fluctuating solar radiation, prediction methods are important for the design of solar energy systems. Theoretical formulae are adequate to predict the range of solar radiation to be expected but do not take into account specific local characteristics and weather conditions. Several methods have been described during the last years to use artificial intelligence as well as statistical approaches to improve solar radiation prediction [2-5].

A solar cell is a device that converts the energy stored in the light to electrical power in a process based on photovoltaic effect [6]. The operation of solar cell correspond to three basic features such generating electron-hole pairs by light absorption, charge carriers separation of opposite type, and separate extraction of those carriers to an external circuit. When the photon of light hit the solar cell and absorbed by material such silicon, electrons are excited and the energy of the electrons can either dissipated as heat inside the material or travel through the cell to reach the conduction band, following this process a current flows through the material to cancel the potential and this electricity is captured [7]. The generated current is direct current (DC) where an inverter can be used to convert the electric power into alternating current (AC). Either the solar cell manufactured for commercial used or research purpose; the solar cell can be classified into three generations. First, second, and third generation are crystalline silicon (polysilicon and monocrystalline silicon), thin film solar cells (silicon, CdTe and CIGS cells) and organic materials thin film technology, respectively [8, 9].

The efficiency of solar cells differs according to the kind of manufactured materials, irradiance, and the environmental circumstances [10]. The efficiencies of the manufactured solar cell generally belong to the standard testing conditions of radiation 1000 W/m^2, temperature 25^o, and air mass 1.5 (AM 1.5) with normal incidence [11]. However, in the real Circumstances, the environmental parameters can affect the efficiency of the solar cell based on the amount of radiation, temperature, humidity, dust, and wind speed [11]. Beside the environmental parameters the atmospheric conditions (such as ground level, water vapor and the zenith angle) can also have an effect on the solar radiation such as intensity and spectrum [10]. It is known that, the solar spectrum is the main factor that can influence the performance of the solar cell which depends on the elevation and inclination of the sun [12]. Because of the environmental and atmospheric effect, sunlight will be reduced by scattering, reflection and absorption; nevertheless, no major reduction can influence the sun radiation in the space between the sun and upper level of the atmosphere. Air mass is the amount of the air above the ground level throughout the earth atmosphere and the air mass coefficient (AM) is the direct sunray path through the atmosphere of the earth and it is suitable to study the reduction effect on solar spectrum through the earth's atmosphere, a simple air mass diagram is showin in figure 1 [13].

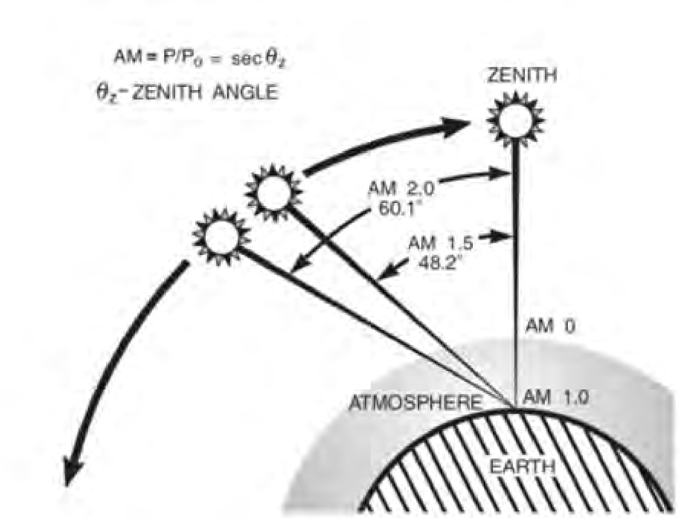

Figure 1. Airmass changes with the zenith angle [13].

2. Model and Results

A semiconductor such as silicon has a valence band and a conduction band. When visible light falls on a thin slab of silicon of thickness "t" the long wavelengths will not have enough photon energy to produce electron-hole pair. Wavelength (λ) that has photon energy equal to the energy gap (E_g) between the valence and conduction bands will produce electron-hole pair such that the electron will not have kinetic energy in the conduction band and so will not dissipate heat in the silicon slab. However short wavelengths that have photon energies larger than the energy gap will produce electron-hole pairs with the electron having kinetic energy which will dissipate heat in the silicon slab.

In this model we assume the energy band gap of silicon in the range of 1.1 eV [14]. And the data [15] of the solar spectral intensity has been plotted in more simplified manner as shown in Figure 2. Figure 2 shows the spectral intensity distribution, $S_{\lambda\ i}(\lambda)$ of the extraterrestrial radiation (AM0) and of the terrestrial radiations (AM1, AM2, and AM3).

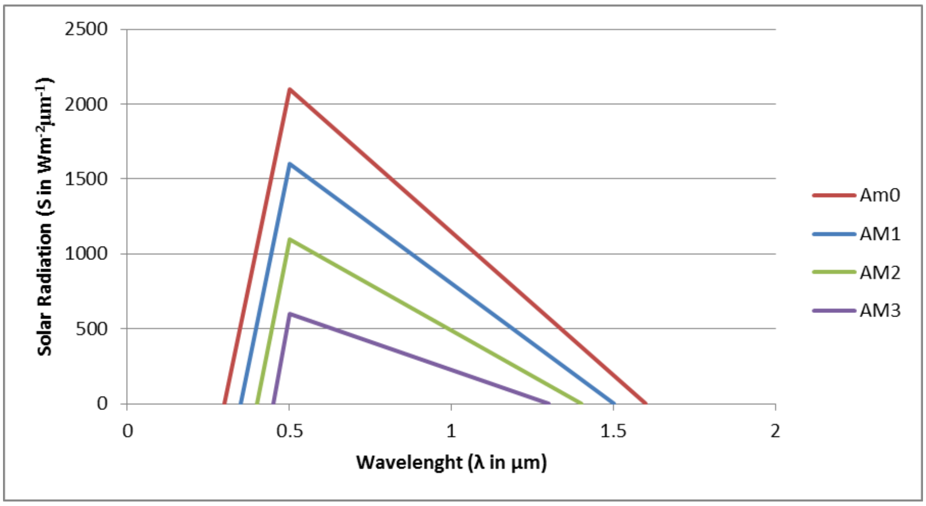

Figure 2. Schematic diagram of the spectral distribution of solar radiation

As we know the spectral distribution coming from the sun is governed by Planck spectral distribution. To simplify matters we assume that the spectral distribution is triangular and as shown in Figure 2. Such simplification makes it possible to analytically calculate the solar cell efficiency. The spectral irradiances at the surface of the earth (AM1, AM2, and AM3) are reduced compared to the extraterrestrial radiation (AM0) due to scattering and absorption of the radiation (light) in the earth's atmosphere. In order to calculate the solar constants we shall use the values of the parameters (solar radiation and wavelength) for different air masses that mentioned in Figure 2 and listed in Table 1 for AM0, AM1, AM2, and AM3.

The equation for the variation of $S_{\lambda\ i}(\lambda)$ is obtained from Figure 2 as follows:

$$S_{\lambda i}(\lambda) = \frac{S_{\lambda mi}(\lambda - \lambda_{oi})}{(\lambda_{mi} - \lambda_{oi})}; \lambda_{oi} < \lambda < \lambda_{mi} \tag{1a}$$

$$S_{\lambda i}(\lambda) = \frac{S_{\lambda mi}(\lambda_{di} - \lambda)}{(\lambda_{di} - \lambda_{mi})}; \lambda_{mi} < \lambda < \lambda_{di} \tag{1b}$$

Where $S_{\lambda\ i}$ is the spectral intensity as a function of wavelength λ corresponds to air mass i, $S_{\lambda\ mi}$ is the maximum solar radiation at wavelength λ and air mass i, λ_{0i} and λ_{di} are the wavelength of air mass i.

To calculate the solar constants G$_{SCi}$ corresponding to i = 0, 1, 2, and 3 we find the area of the various triangles using the formula:

$$G_{SCi} = \frac{S_{\lambda mi}(\lambda_{di} - \lambda_{oi})}{2} \tag{2}$$

The values of G$_{SCi}$ for AMi (i = 0, 1, 2, 3) as calculated from Eq. 2 are listed in Table 1.

Table 1. The solar intensities, wavelength, and solar constant correspond to different air masses

i	(Wm-2μm-1)	(μm)	(μm)	(Wm-2)
0	2100	0.3	1.6	1365
1	1600	0.35	1.5	920
2	1100	0.4	1.4	550
3	600	0.45	1.3	255

The losses in solar radiation are of two types. Type 1 is due to photons with energy, E, lesser than the energy gap (E_g) and will not produce any conduction electrons and so will not be absorbed by the material. Type 2 losses are due to photons with energy, E, greater than the gap energy, E_g, where each photon produces a conduction electron, and the excess energy (E – E_g), goes to increase the kinetic energy of the conduction electron which heats up the material.

Type 1 loss can be calculated from the triangle in Figure 2. The area under the curve between λ_{di} and λ_{0i} represents type 1 loss and it is given by:

$$\triangle S_{1i} = \frac{S_{\lambda gi}(\lambda_{di} - \lambda_{oi})}{2} \tag{3}$$

And due to similarity of trian1gles we have:

$$\frac{S_{\lambda mi}}{S_{\lambda gi}} = \frac{\lambda_{di} - \lambda_{mi}}{\lambda_{di} - \lambda_{gi}} \tag{4}$$

Therefore, Eq. (3) becomes

$$\triangle S_{1i} = \frac{S_{\lambda mi}(\lambda_{di} - \lambda_{oi})^2}{2(\lambda_{di} - \lambda_{mi})}$$

As for type 2 losses $\triangle S_{2i}$these are calculated as follows. The excess energy *$(E – E_g)/E$ for $E>E_g$* can be calculated from the relation:

$$(\frac{1-E_g}{E})S_{\lambda i} = (\frac{1-\lambda}{\lambda_g})S_{\lambda i} = S^{/}_{\lambda i};\lambda_{oi} < \lambda < \lambda_g \tag{6}$$

Where we have used the relation that relates the photon energy given in $\mu m.eV$to its wavelength:

$$E = 1.24/\lambda \tag{7}$$

Therefore, from Eq. (6) we notice that for $\lambda = \lambda g$, $S^{/}_{\lambda\ i} = 0$. Also for $\lambda = \lambda_{0i}$ we know that $S_{\lambda\ i}(\lambda_{0i})$ is zero from Eq.(1a) above, and therefore $S^{/}_{\lambda\ i}(\lambda_{0i}) = 0$ from Eq. (6). For $\lambda = \lambda_{mi}$, $S^{/}_{\lambda}$ acquires the value $S^{/}_{\lambda\ m} = S_{\lambda\ Mi}(1\text{-}\ \lambda_{mi}/\ \lambda_g)$. Substituting S$\lambda$i from Eq.(1a & 1b) into Eq. (6) will lead to a quadratic dependence of S λi' on λ. Plotting Eq. (6) in conjunction with Eqs.(1a & 1b) will give us a curve that has a negative curvature with a maximum for the interval, $\lambda_{0i}<\lambda<\lambda_{mi}$, and a positive curvature with a minimum for the interval, $\lambda_{mi}<\lambda<\lambda_g$. This situation can be exploited to approximate Eq. (6) with a triangle that starts at $\lambda=\lambda_{0i}$ and rises to the peak at $\lambda=\lambda_{mi}$ and descends and terminates at $\lambda=\lambda_g$. This approximation has ignored the area between the straight line and the positive curvature parabola in the interval, $\lambda_{0i}<\lambda<\ \lambda_{mi}$, and has added an approximately compensating area in the interval, $\lambda_{mi}<\lambda<\lambda_g$. The area of this triangle which is the loss due to excess energy, ΔS_{2i}, is given by:

$$\triangle S_{2i} = \frac{S_{\lambda mi}(1 - \lambda_{mi}/\lambda_g)(\lambda_g - \lambda_{oi})}{2} \tag{8}$$

Of course the energy delivered to an electron is not E_g rather it is of the order of eV_{max} where V_{max} is the maximum voltage at the operating point at which the photovoltaic cell is functioning. Experimentally the ratio of eV_{max}/E_g = 0.45/1.1 and the solar cell efficiency (h_i) is defined to be the ratio of the useful electric power (P_{el}) to the available optical power (P_{op}), that is:

$$\eta_i(AM_i) = \frac{P_{el}}{P_{op}} \tag{9}$$

For the values given and calculated for AM*i* we find:

$$\eta_i(AMi) = \frac{(eV_{max}/E_g)G_{sci}(1 - (\triangle S_{1i} + \triangle S_{2i})/G_{sci})}{G_{sci}} \tag{10}$$

Inserting the appropriate values obtained from Table 1, into Eq. (10) we get the values for the efficiencies listed in table 2. We notice that efficiency of the solar cell is on the average around 20%. Of course improving the intrinsic efficiency of the PV cell will improve its overall efficiency.

Table 2. The values of the efficiencies obtained from Eq. (10) based on the suggested model.

AM$_i$	S$_{\lambda\ mi}$ (Wm$^{-2}\mu$m^{-1})	λ_0 (μm)	λ_d (μm)	G$_{sci}$ (Wm^{-2})	ΔS$_{1i}$ (Wm^{-2})	ΔS$_{2i}$ (Wm^{-2})	η_i
0	2100	0.3	1.6	1365	17.5	33.6	20.00
1	1600	0.35	1.5	920	13.9	35.6	20.66
2	1100	0.4	1.4	550	10	38	21.19
3	600	0.45	1.3	225	5.9	41.7	21.44

3. Conclusion

In this work, a model to present the solar cell efficiency in relation with air mass effect has been developed. The final efficiencies have been derived from the relation based on global solar radiation and the type of losses in solar radiation inside the solar cell that correspond to the type of air mass. Based on the presented model, the results showed that the efficiency of the solar cell in the average of 20%.

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