Exergy Modeling of Monocrystalline Silicon Solar Cells with Spectral Irradiation Variations

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Abstract. Exergy modeling was made to analyze the work performance of monocrystalline silicon solar cells. Analysis is done by making modeling and simulation of the equation and parameter data that affect the amount of photon energy and the exergy rate at PV. The incident radiation source used varies on the (0.05, 0.1, 0.3 and 0.5 Suns) in the AM1.5G spectral response standard. Calculation analysis with the model made shows that the PV module photonic energy is greater than the photonic exergy, this is related to the irreversibility of the PV module conversion system.

1. Introduction
Solar radiation that falls directly to earth is only 70%, partly blocked by the ozone layer, the upper dust layer, air molecules, water vapor and the lowest dust layer will then be absorbed, reflected and transmitted on the earth's surface [1]. The amount of energy received by the earth from the sun is estimated at $1.73 \times 10^{14}$ kW. Energy in the form of photons in the form of electromagnetic waves consists of ultraviolet (200 - 400 nm), visible light (400 - 700 nm) and infrared (700 – 3000 nm). While the amount of power received above the atmosphere is relatively constant and an estimated 1368 kW/m$^2$ is called the solar constant. Photons in visible light with wavelengths between 400 - 700 nm which are most absorbed by photovoltaics [2].

Photovoltaics is a technology in the form of semiconductors that can convert photon energy into electrical energy. The electricity generated is very environmentally friendly and clean, this is in line with the goal of the 2030 Sustainable Development Goals (SDGs) concept that is affordable and clean energy. All countries have agreed on global actions to end poverty, reduce inequality and protect the environment [3]. When solar energy in the form of photons hits the semiconductor material, the photons will be reflected, absorbed or transmitted, where for valence electrons the atoms absorbing photons will experience an increase in energy and will jump into the conduction band as free electrons. The photovoltaic effect is produced from the absorption of sunlight photons in the p-n linking region which produces an electron-hole pair, due to the emergence of an electric field in the p-n linking region causing a potential difference due to the separation of electric charge, where electrons will move to the n-type region and the hole will move to the p-type region. If both are connected and connected to the load, there will be an electric current during the Sun's light on the surface of the connection p-n [4].
An analysis of the performance of PV cells has been carried out by, [5, 6] which shows the output power and efficiency are very dependent on cell temperature and solar irradiation. They do modeling and simulation to see the effect of variations in the intensity and temperature of the cells being input, but in research conducted energy lost due to processes is not shown and explained. We can find out this energy loss by developing the concept of exergy in the analysis of Law II Thermodynamics, energy lost from the system associated with thermodynamic processes that occur in PV systems can we find out the information [7]. The second law of thermodynamics explains that the total entropy of an isolated thermodynamic system tends to increase with time, close to its maximum value. Exergy efficiency is expressed as the difference from electrical energy and thermal energy in the form of maximum effort done by a thermodynamic system when it is going to a reversible process directing the system to a state in balance with its environment [8]. Therefore in this paper we will review the effect of environmental parameters, namely solar irradiance on PV performance by conducting analyzes based on energy reviews and exergy in the form of photonic energy spectrum of sunlight reaching the surface of the PV modules.

2. Research Methods

2.1. Photon Energy

Solar energy can be called photonic energy from the sun and this energy moves in the form of photons. A photon is characterized by a wavelength, while the value of a photon energy stands at a specific wavelength [9]. The photon energy in Joule can be calculated as follows [10]:

\[
E_{\text{ph}}(\lambda) = \frac{hc}{\lambda}
\]

Where \(E_{\text{ph}}(\lambda)\) is the energy of the photon, \(h\) and \(c\) are constants; \(h\) is Planck's constant \((6.626 \times 10^{-34} \text{ J.s})\); \(c\) is the speed of light \((2.998 \times 10^8 \text{ m/s})\); and \(\lambda\) is the wavelength of the light spectrum.

2.2. Exergy Analysis

Exergy is defined as the maximum amount of work that can be done by a system or flow of matter or energy when it comes to equilibrium with the reference environment. Exergy Analysis is a technique that uses mass conversion and conversion of energy principles along with the second law of thermodynamics for the analysis, design, and improvement of energy systems and other analog systems[11].
To evaluate the quality of a power system using exergy analysis, one defines exergy efficiency with the following expression:

\[
\eta_{ex} = \frac{W_u}{W_{ua}} = \frac{W_u}{W_{ua}}
\] (2)

\[
W_{ua} = E_x^1 - E_x^2
\] (3)

\[
W_u = E_x^1 - E_x^2
\] (4)

or, in the case of loss of exergy (as a result of an irreversible process) can be stated as follows:

\[
\eta_{ex} = 1 - \frac{E_{x_{loss}}}{E_x^1 - E_x^2}
\] (5)

\[
E_{x_{loss}} = W_{ua} - W_u = E_x^1 - E_x^2 - W_u
\] (6)

\[
E_{x_{loss}} = W_{ua} - W_u = E_x^1 - E_x^2 - W_u
\] (7)

Based on the photon energy reaching the surface of the PV module, the analysis of the energy and exergy of the PV module is based on the photonic energy expressed in the equation (8 – 13).

\[
N_{ph} = \left( \frac{4.4 \times 10^{21}}{1367} \right) G
\] (8)

\[
\dot{E} n_{ph} = E n_{ph}(\lambda) N_{ph} A
\] (9)

\[
E n_{chemical}(\lambda) = E n_{ph}(\lambda) x \left( 1 - \frac{T_a}{T_c} \right)
\] (10)

\[
T_c = T_{amb} + \frac{G}{0.8}(NOCT - 20')
\] (11)

\[
E x_{chemical} = \eta_{pc} E n_{chemical}
\] (12)

\[
\eta_{pc} = \frac{VI}{G A}
\] (13)

Where \( N_{ph} \) is the number of photons arriving at the surface of the PV modules of time and area; \( E n_{ph}(\lambda) \) is photonic energy; \( E n_{chemical}(\lambda) \) is the chemical potential (W); \( E x_{chemical} \) is the exergy rate available from the chemical potential (W); \( T_c \) is the sun’s surface temperature (5777 K); \( T_{amb} \) is the ambient temperature; \( T_c \) is the temperature of the PV cell; \( \eta_{pc} \) is the efficiency of PV conversion; \( V \) is the output voltage (V); \( I \) is the output current; \( G \) is solar irradiation (W/m²) and \( A \) is the surface area of PV (m²).

3. Results and Discussion

3.1. Modeling and Simulation in Simulink Matlab

Energy and exergy analysis is carried out by modeling and simulating data parameters that affect PV performance. Equations 8-13 are simply modeled to easily determine the magnitude of photon energy
and the exergy rate, which will then be converted into a block diagram on a Simulink Matlab. The input parameters used include the specification of PV monocrystalline silicon [12], variations in irradiation, cell temperature, and environmental temperature. The results of the simulation will be explained in the form of images and graphics.

**Figure. 2 Variations in AM1.5 Global Spectrum Data**

Figure 2 shows the variation of irradiation spectrum data inputted (0.5, 0.3, 0.1 and 0.05 Suns) with the amount of power generated (448.98, 269.39, 87.79 and 44.89 W/m²). The magnitude of the generated spectrum power is then inputted into the modeling and simulation on the Matlab Simulink block diagram to obtain the current and voltage values.

**Figure. 3 Block diagram of equation 8-13**

Figure 3 shows the results of modeling with a block diagram on a Matlab Simulink. Equations 8-13 are input one by one. Based on Quantum Theory, sunlight can be considered as an energy package in the form of photons that have energy that depends on the frequency or color of light. When it reaches the surface of the PV module, the photon will interact with the material, so that the valence electrons of the atom that absorbs the photon will experience an increase in energy and will jump to the band.
The number of photons reaching the PV surface depends on the irradiance $G$, where the greater the value of the input, the greater the number of photons reaching to be converted into electricity. The simulation results are shown in Table 1. The energy analysis and exergy of the PV module is based on calculations using a constant wavelength of 400 nm. The results are shown in Figure 4 which explains the photonic energy (chemical potential) and exergy associated with the photonic energy of the PV module. The effect of the wavelength of sunlight in the visible light spectrum region will cause the energy value (chemical potential) and exergy (exergy rate available from chemical potential) to be large.

The results of the analysis show that the photonic energy of the PV module is greater than the photonic exergy, this is related to the irreversibility process related to the actual state of the conversion system that takes into account the exergy lost during the process, for example heating the module to be discharged into the environment.

### 4. Conclusion

The energy and exergy analysis results of PV modules based on photonic energy are strongly influenced by the wavelength spectrum of light reaching the surface of the PV module and correlating...
directly with the intensity of solar irradiance related to the number of photons involved in the conversion process. The analysis shows that during the conversion process photonic energy is always greater than photonic exergy this is due to the irreversibility process related to exergy lost due to conversion into other forms of exergy, for example heating modules that will be discharged into the environment.

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