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Factors affecting photovoltaic cell efficiency: A theoretical analysis

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ABSTRACT : *A solar cell, also known as a photovoltaic cell, is an apparatus that uses sunlight to directly produce electricity. However, a number of reasons may contribute to its low operational efficiency. This paper covers therefore the most essential elements that determine the efficiency of solar cells which are: Cell Temperature, Maximum Power Point Tracking (MPPT) and Energy Conversion Efficiency. Optimizing these variables would undoubtedly increase solar cell efficiency for a more dependable use case.*

KEYWORDS: *Solar Cell, Cell Temperature, Maximum Power Point Tracking, Energy Conversion Efficiency*

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I. INTRODUCTION

Solar Energy is energy that originates from the sun. Solar cells are constructed of various semi conductive materials. Materials that function as insulators at low temperatures but become electrically conductive when exposed to light or heat are known as semiconductors.

Light photons impart their energy to the charge carriers as they strike the cell. Photogenerated positive charge carriers (holes) and their negative counterparts (electrons) are separated by the electric field across the junction. When the circuit is closed on an external load, an electrical current is thus withdrawn. The efficiency of solar cells is influenced by several factors. This study looks at the variables that influence solar cell efficiency based on research findings. These variables include energy conversion efficiency for solar cells, utilizing the MPPT with solar cells, and varying cell temperature, depletion, forest degradation, and radioactive material emissions are linked to issues with energy supply and consumption. A decrease in the usage of fossil fuels, an increase in ecologically friendly energy sources, and energy conservation through increased energy efficiency are among potential remedies that have emerged to stop these consequences.

Light photons impart their kinetic energy to the charge particles as they strike the cell. Photogenerated carriers with positive charges (holes) and their negative counterparts (electrons) are separated by the field of electricity across the junction. When the circuit closes on an external load, an electrical current is thus withdrawn. The efficiency of solar cells is influenced by several factors.

This analysis looks at the variables that influence solar cell efficiency based on research findings. These variables include energy conversion efficiency for solar cells, utilizing the MPPT with solar cells, and varying cell temperature [1],toxicity to humans, provides 92 to 97 a percentage less to acid rain, and contributes 97 to 98 percent less to marine pollution than electrical power generated from 100 percent coal. Photovoltaic electricity also contributes 96 to 98 percent less greenhouse effect gases than electricity created from 100 percent coal and 92 to 96 percent less than the European electricity mix [2].

Photovoltaic-generated electricity does not pollute the air or water, deplete resources from nature, or pose a health risk to humans or animals. The only possible drawbacks are related to certain hazardous compounds employed in the manufacturing process, such as arsenic and cadmium. Recycling and appropriate disposal can readily mitigate these small environmental effects [3].

Characterization of Photovoltaic Cells

The P-type and N-type semiconductors, which have distinct electrical characteristics, are combined to form a solar cell. The P-N junction is the joint that forms between these two semiconductors. The photovoltaic cell absorbs sunlight that strikes it. The absorbed light's energy creates positively or negatively charged particles (holes and electrons) that are free to travel or shift in any direction inside the cell. N-type semiconductors have a tendency to accumulate electrons (-), while P-type semiconductors tend to accumulate holes (+). Consequently, electricity flowing in the cell when a load from outside, like an electric motor or lightbulb, is linked across the front and rear electrodes [4].

A schematic of the layers of a typical PV cell is shown in Fig.1 below.

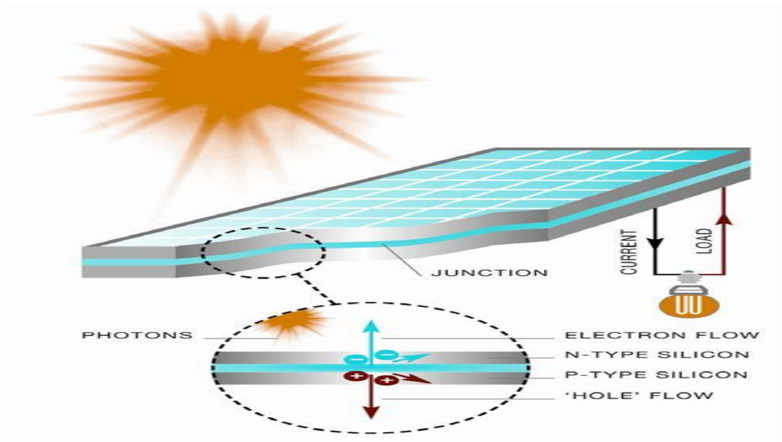

Fig 1: A typical PV cell (*Google picture. Source: EPIA*)

The semiconductor material has to be able to absorb a large part of the solar spectrum. Dependent on the absorption properties of the material the light is absorbed in a region more or less close to the surface. When light quanta are absorbed, electron hole pairs are generated and if their recombination is prevented, they can reach the junction where they are separated by an electric field.

The photoelectric effect was first noted by a French physicist, Edmund Bequerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. The theory of the solar cell is the solar effect of semiconductor material. The solar effect is a phenomenon that the semiconductor material absorbs the solar energy, and then the electron-hole excited by the photon separates and produces electro motive force [5].
The *I-V* characteristic of the solar cell changes with the sunshine intensity $S(Wm^2)$ and cell temperature t (ºC), that is $I = f(V, S, t)$. According to the theory of electronics, when the load is pure resistance, the actual equivalent circuit of the solar cell is as Fig. 2.

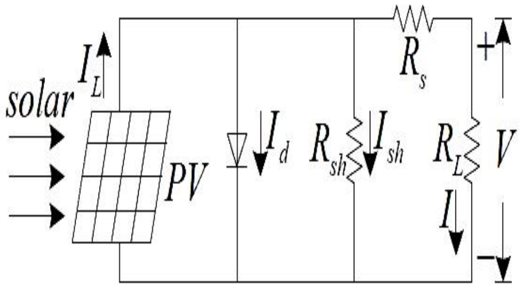

Fig 2: The equivalent circuit of the solar cell (Source: www.seekic.com)

I_L is current supplied by solar cell.

$$I = I_L - I_0\left[exp\left(\frac{q(V+IR_S)}{AkT}\right) - 1\right] - \frac{V+IR_S}{R_{SH}} \qquad (1)$$

$$I_d = I_0\left[exp\left(\frac{q(V+IR_S)}{AkT}\right) - 1\right] \qquad (2)$$

Where: I_d is the junction current of the diode, I is the load/current, I_L is the photovoltaic current, I_O is the reverse saturation current, q is electronic charge, k is the Boltzmann constant, T is absolute temperature, A is factor of the diode quality, R_S is the series resistance, and R_{SH} is the parallel resistance.

Another important parameter is open circuit voltage $V_{OC,}$

$$V_{OC} = KT/q \ln(I_L/I_O + 1) = KT/q \ln(I_L/I_O) \qquad (3)$$

Fig.3 below shows an I-V characteristic together with the power curve, to illustrate the position of the maximum power point.

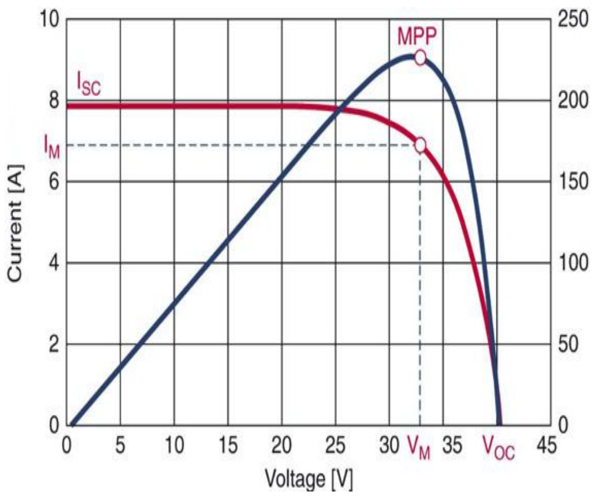

Fig. 3: Typical I-V and Power characteristic of a crystalline silicon module (Source: www.solarinnova.cn)

Factors affecting Solar Cells Efficiency

Cell Temperature

As temperature increases, the band gap of the intrinsic semiconductor shrinks, and the open circuit voltage (V_{OC}) decreases following the p-n junction voltage temperature dependency of seen in the diode factor q/kT. Solar cells therefore have a negative temperature coefficient of V_{OC} (β). Moreover, a lower output power results given the same photocurrent because the charge carriers are liberated at a lower potential. Using the convention introduced with the Fill Factor calculation, a reduction in V_{OC} results in a smaller theoretical maximum power *max* $P_{max} = I_{SC}$ X V_{OC} given the same short-circuit current I_{SC}.

As temperature increases, again the band gap of the intrinsic semiconductor shrinks meaning more incident energy is absorbed because a greater percentage of the incident light has enough energy to raise charge carriers from the valence band to the conduction band. A larger photocurrent results; therefore, I_{SC} increases for a given isolation, and solar cells have a positive temperature coefficient of I_{SC} (α).

Fig.4 shows the I-V and P-V characteristics at the constant illumination when the temperature changes.
Temperature effects are the result of an inherent characteristic of crystalline silicon cell-based modules. They tend to produce higher voltage as the temperature drops and, conversely, to lose voltage in high temperatures. Any solar panel or system derating calculation must include adjustment for this temperature effect.

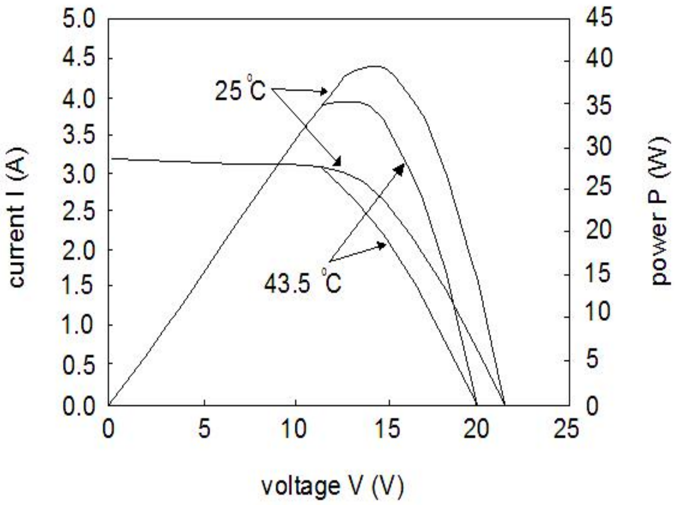

Fig. 4: I-V and P-V characteristics of solar cell module (Source: www.solarinnova.cn).

Maximum Power Point Tracking

Currently, the electricity transformation efficiency of the solar cells is very low of the value of about 14%. The efficiency of solar cells should be improved with various methods. One of them is maximum power point tracking (MPPT) which is an important method. The MPPT operates with DC to DC high efficiency converter that presents an optimal and suitable output power.
The resulting I-V characteristic is shown in Fig.5.

The photo generated current I_L is equal to the current produced by the cell at short circuit (V= 0). The open circuit Voltage V_{OC} (when I = 0) can easily be obtained.
No power is generated under short or open circuit. The maximum power P produced by the conversion device is reached at a point on the characteristic. This is shown graphically in Fig.5 where the position of the maximum power point represents the largest area of the rectangle shown.

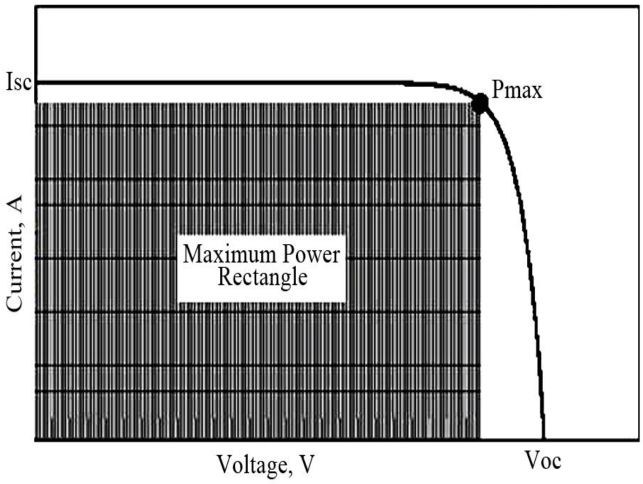

Fig.5: The I-V characteristic of an ideal solar cell (Source: www.ni.com)

One usually defines the fill-factor, *ff by:*

$$ff = \frac{P_{\max}}{V_{OC}} = \frac{V_m I_M}{V_{OC} I_L} \quad (4)$$

Where: V_m and I_m are the voltage and current at the maximum power point.
When the output voltage of the photovoltaic cell array is very low, the output current changes little as the voltage changes, so the photovoltaic cell array is similar to the constant current source; when the Voltage is over a critical value and keeps rising, the current will fall sharply, now the photovoltaic cell array is similar to the constant voltage source. As the output voltage keeps rising, the output power has a maximum power point. The function of the maximum power tracker is to change the equivalent load taken by the photovoltaic cell array, and adjust the working point of the photovoltaic cell array, in order that the photovoltaic cell array can work on the maximum power point when the temperature and radiant intensity are both changing.

Energy Conversion Efficiency

A solar cell's energy conversion efficiency (η, "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the maximum power point, P_m, divided by the input light irradiance (E, in W/m^2) under standard test conditions and the surface area of the solar cell (Ac in m^2)

$$\eta_{\max} = \frac{P_{\max}}{E \times A_C} \quad (5)$$

Where: $\eta_{\max}$ is the maximum efficiency, $P_{\max}$ is the maximum power output, E is the incident radiation flux and A_C is the area of collector.

The efficiency of energy conversion is still low, thus requiring large areas for sufficient insulation and raising concern about unfavorable ratios of energies required for cell production versus energy collected.
In order to increase the energy conversion efficiency of the solar cell by reducing the reflection of incident light, two methods are widely used. One is reduction of the reflection of incident light with an anti-reflection coating, and the other is optical confinements of incident light with textured surfaces. They showed that the transformation of the wavelength of light could significantly enhance the spectral sensitivity of a silicon photodiode from the deep UV and through most of the visible region.

The solar module has a different spectral response depending on the kind of the module. Therefore, the change of the spectral irradiance influences the solar power generation
The solar spectrum can be approximated by a black body of 5900 K which results in a very broad spectrum ranging from the ultraviolet to the near infrared. A semiconductor, on the other hand can only convert photons with the energy of the band gap with good efficiency.

Photons with lower energy are not absorbed and those with higher energy are reduced to gap energy by thermalization of the photo generated carriers. Therefore, the curve of efficiency versus band gap goes through a maximum as seen from Fig. 6 below.

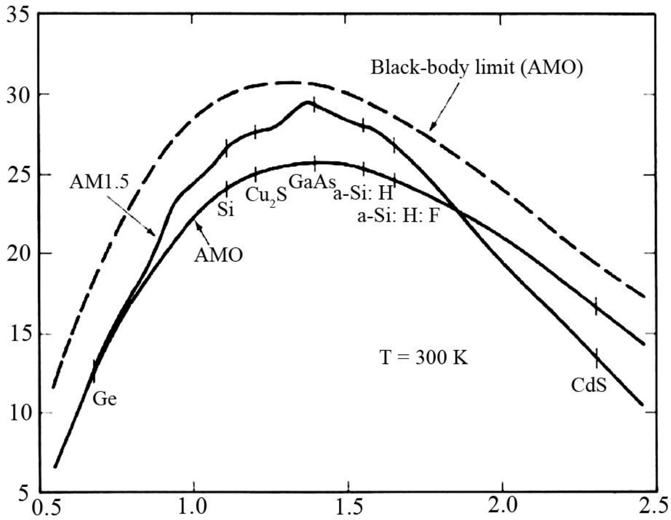

Fig.6: Dependency of the conversion efficiency on the semiconductor band gap
(Source: www.pubs.rsc.org).

II. CONCLUSION

This paper examined factors that affect the efficiency of solar cells. These are changing of cell temperature, using the MPPT with solar cell and energy conversion efficiency for solar cell. Temperature effects are the result of an inherent characteristic of solar cells. They tend to produce higher voltage as the temperature drops and, conversely, to lose voltage in high temperatures. The energy conversion efficiency is increased by reducing the reflection of incident light. The function of the maximum power tracker is to change the equivalent load taken by the solar cell array, and adjust the working point of the array, in order to improve the efficiency. Changing of these factors is very critical for solar cell efficiency. The optimum factors make it possible to get the great benefits of solar electricity at a much lower cost.

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