Determination of photoelectric properties of silicon-based solar cells using the edibon device

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Abstract: The current issue of the present era is the development of renewable energy sources due to the increasing demand for energy resources and the limitation of traditional fuel sources. In this article, the main photovoltaic parameters of silicon-based solar cells were determined experimentally using the Edibon educational laboratory device. During the research, the current-voltage and power-voltage characteristics of the solar cell were measured under various illumination conditions. Based on the experimental results, important photovoltaic parameters such as short-circuit current, open-circuit voltage, maximum power point, filling factor and useful work coefficient were calculated. The results obtained using the Edibon device were compared with theoretical values, and the dependence of the efficiency of silicon-based solar cells on illumination intensity and temperature was analyzed. The results of the research are of great importance for improving the educational process in the field of renewable energy sources and in-depth study of the performance characteristics of solar cells.

Keywords: silicon-based solar cell, photovoltaic parameters, Edibon device, current-voltage characteristic, useful work coefficient, filling coefficient, solar energy, renewable energy

Introduction. Over the past two centuries, technological innovation and population growth have led people around the world to become accustomed to high energy consumption. Currently, the demand for energy is growing rapidly worldwide. Energy consumption is increasing, and non-renewable petroleum reserves are dwindling. We have already seen the impact of high energy consumption on the global, regional and local levels. Fossil fuel energy sources have led to a steady increase in the pollution of water, land and atmosphere with nitrogen oxides, sulfur dioxide and methane. Carbon dioxide (6.3 trillion tons in 1988) is the most abundant component of the greenhouse gases released during the combustion of fossil fuels. Such an impact on the atmosphere could lead to a warming of 1.5 to 4.5 degrees Celsius by the middle of the next century. This warming has potentially devastating consequences for agriculture, forests, wildlife, coastal communities, and the overall quality of human life. With the rapid growth of energy consumption and the environmental degradation caused by the use of fossil fuels, the search for alternatives to fossil fuels was inevitable. In terms of the social costs of energy use, renewable sources have long been superior to fossil fuels and nuclear energy. With the available technology and the increasing cost of renewable energy, it is time to start using more sustainable energy.

Solar energy is one of the most environmentally friendly, unlimited and economically promising energy sources. Silicon-based solar cells are widely used in the conversion of solar energy into electricity, and their high reliability and technological convenience occupy a leading position in the industry. The efficiency of silicon-based solar cells is directly related to their photovoltaic parameters - open circuit voltage, short circuit current, maximum power, fill factor and useful work coefficient. Determining and analyzing these parameters is of great importance for a deep understanding of the mechanism of operation of solar cells and developing ways to increase their efficiency.

The photovoltaic (PV) effect is the electrical potential that arises when a common junction of two dissimilar materials is illuminated by photon radiation. Thus, photovoltaic elements convert light directly into electrical energy.

The physics of photovoltaic elements is very similar to the properties of a classical diode with a p-n junction. When light is absorbed by a photovoltaic element, the energy of the absorbed photons is transferred to the electronic system of the material, as a result of which charge carriers are released at the contact site. The charge carriers can be electron-ion pairs in liquid electrolytes or electron-hole pairs in solid semiconductor materials. The charge carriers in the contact area create a potential gradient, which is accelerated by the electric field and causes the flow of charges through an external circuit (i.e., a current is generated). The square of the resulting current is multiplied by the resistance of the contact (I2R), which forms the circuit, thereby converting light into electrical energy. The remaining energy of the photon increases the temperature of the photovoltaic cell. The potential of photovoltaic materials lies in the difference in chemical potential between two isolated electrons, called the Fermi level. When they are connected, the contact approaches a new thermodynamic equilibrium. Thermodynamic equilibrium can only be achieved when the Fermi level is the same for both materials. This occurs due to the transfer of electrons from one material to the other until a potential difference is established between the two materials, which have a potential equal to the difference in the initial Fermi level. This potential drives the photocurrent.

Research methods. There are metal contacts on both sides to collect the photocurrent. The lower (dark) contact side of the photocell collects the electric current generated when the photon induces the photon, and the upper contact is made of a superconducting material. The thin superconducting layer on the remaining upper surface collects the flow of charges and transmits light. The distance between the superconductor and the conductor in the contacts determines the trade-off between maximizing electrical conductivity and minimizing light blocking. In addition to the basic elements, several features are also included in the design to ensure good performance. For example, the front of the camera has a coating that reduces light reflection to allow as much light in as possible, and is covered with a transparent adhesive cover slip, providing mechanical protection.

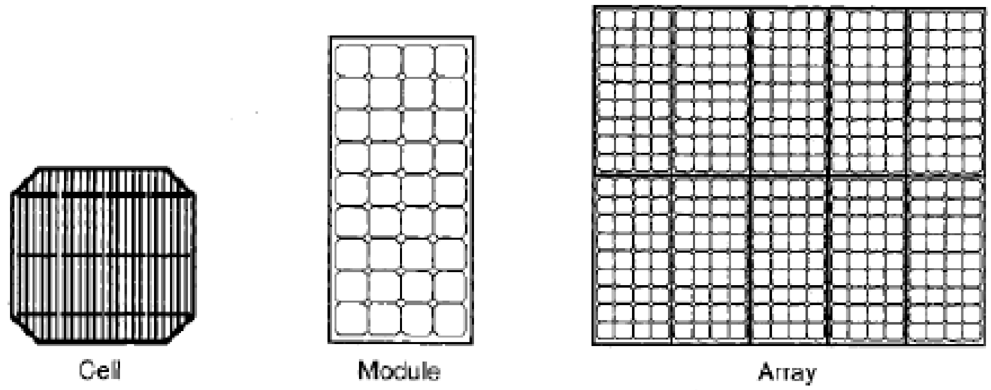

Figure 1. General construction of a solar cell and its connection

The solar cell system described above is the basic building block of photovoltaic energy. Typical solar cells are a few square inches in size and produce about one watt of electricity. To achieve high power, many of these cells are connected in series and parallel circuits in a panel (module) with an area of several square meters. A solar array is defined as a group of several modules/panels electrically connected in series-parallel combinations to produce the required current and voltage. When installed on a roof, the modules are usually laid directly on the roof. With the development of amorphous silicon technology, it is possible to convert the traditional models of PV cells into models that can replace them one by one, saving material and labor. Electrical equivalent circuit of the Edibon system:

The complex physics of a solar cell can be represented by the equivalent electrical circuit shown in the figure below

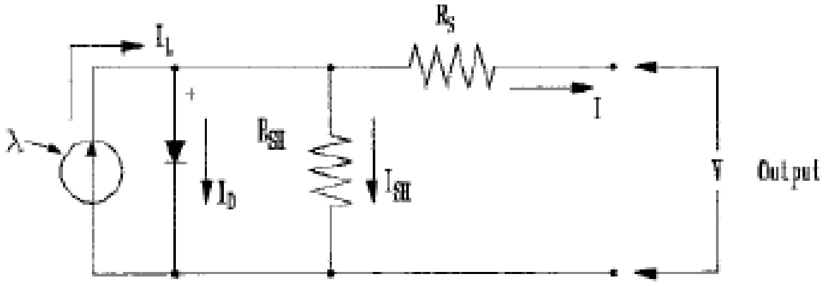

Figure 2. Electrical equivalent circuit diagram of the Edibon system.

The circuit parameters are as follows. The output current (I) is the light-emitting current (IL) through the diode (ID) plus the shunt resistance (ISH). The series resistance (RS) is the internal resistance of the circuit and depends on the depth of the p-n junction, impurities, and contact resistance. The shunt resistance (RSH) is inversely proportional to the current in the photovoltaic cell. In ideal photovoltaic cells, RS = 0 (no series losses) and RSH = ∞ (nearly zero current). Typically, high-quality silicon photovoltaic cells of one square inch have RS = 0.05 to 0.10 Ohms and RSH = 200 to 300 Ohms. The photovoltaic conversion efficiency is sensitive to small changes in RS but not to RSH. A small increase in R can significantly reduce the PV output. In the equivalent circuit, the current supplied to the external load is equal to the current produced by the light (IL), the current in the diode (ID), and the current in the shunt resistor (ISH). The operating voltage (Voc) of the photovoltaic cell is obtained when the current in the resistor is zero

(i.e. I = 0) and is defined as: $V_{oc}=V+IR_{SH}$ (1)

The total current in the diode is given by the classical expression for the diode:

$$I_d = I_D\left[\frac{QV_\infty}{AKT}-1\right] \quad (2)$$

Where: I_D=current through the diode

Q=electron charge

A=constant in the linear relationship

T=temperature (K)

Therefore, the current through the resistor is expressed as

$$I = I_L - I_D\left[e^{\frac{QV_{OC}}{AKT}}-1\right]-\frac{V_{OC}}{R_{SH}} \quad (3)$$

The last term, the shunt resistance current, is small in practical photovoltaics compared to IL and ID and can be neglected. Thus, the saturation current of a diode can be determined experimentally by applying a voltage Voc in the dark and measuring the current flowing through the photovoltaic cell. This saturation current of a diode is often called the dark current or reverse current.

Results. The two most important parameters widely used to characterize the electrical properties of a cell are the on-state voltage (Voc) and the short-circuit current (Isc). The short-circuit current is measured by shorting the output elements and measuring the photovoltaic cell current under full illumination. If we ignore the actions of the small diode and the current in the circuit at zero voltage, the short-circuit current in this case is equal to the photocurrent, reaching a maximum value (IL). The maximum photovoltaic is generated at the on-state voltage. However, ignoring the current flowing through the open circuit, the equation for the pure operating voltage at I = 0 gives the following unimpeded voltage:

$$V_{OC} = \frac{AKT}{Q} Log_n \left(\frac{I_L}{I_D} + 1 \right) \quad (4)$$

The formula for constant voltage (KT/Q) is for normal temperature (300 ° K = 0.026 volts). In practical photovoltaic cells, the photocurrent (IL) is several times greater than the reverse saturation current (ID). Therefore, the operating voltage is many times greater than the value of (KT/Q). Considering constant illumination, IL/RD is a function of the temperature of the photovoltaic cell and usually indicates the temperature coefficient at which the solar cell becomes negative open circuit.

I-V and P-V curves. The electrical characteristics of a photovoltaic cell are usually represented by a current-voltage curve (I-V).

The output power of the panel is the product of the output voltage and the current.

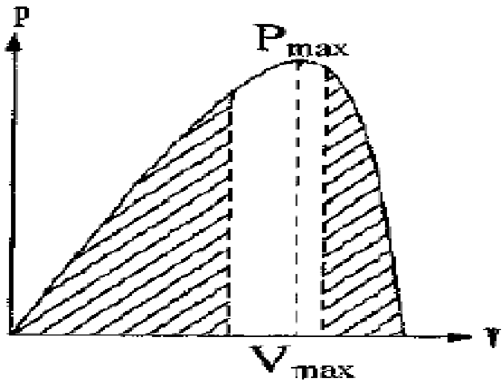

Figure 3 Power vs. Voltage of a Solar Cell

Figure 3 shows the power vs. voltage function. A photovoltaic cell does not produce power at zero voltage or zero current, and produces maximum power at the voltage corresponding to the breakpoint of the I-V characteristic. Therefore, photovoltaic power circuits are designed so that the modules operate close to the inflection point, slightly to the left. Photovoltaic modules are roughly modeled as a constant current source in power system analysis

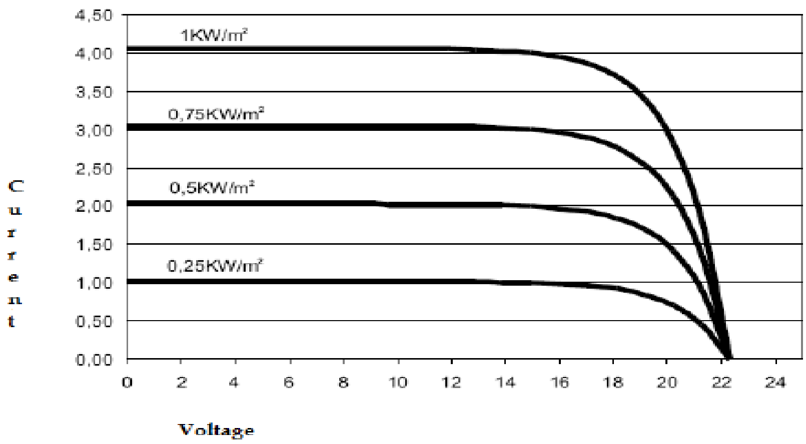

Figure 4 Solar panel at different power levels VAXi for 25 C

The figure shows the I-V curves of a 66 W panel (at four intensities of solar irradiation: 1000 W/m2, 750 W/m2, 500 W/m2 and 250 W/m2). These curves are for AM1.5 (air mass 1.5). Zero air mass (AM0) represents the conditions in space with a solar radiation of 1350 W/m2. AM1 represents the ideal state of the model (clean and dry air, clear sky, noon). The air we find on a typical day with average humidity and air pollution, when sunlight experiences the least resistance to reach the ground, is AM1.5, which is taken as the starting value. On a normal clear day with AM1.5, the solar energy intensity is about 1000 W/m2. On a cloudy day, it is lower (about 500 W/m2). Solar intensity is another metric that the industry uses for reporting.

The photoconversion efficiency of a photovoltaic cell is defined as:

$$\eta = \frac{elektrquvvati}{tushayotganquyoshquvvati} \quad (5)$$

Obviously, higher efficiency leads to higher power output for a given amount of light.

Factors affecting solar panel design:

1. Intensity of solar radiation.
2. Angle of the sun line or slope of the solar panel.
3. Matching resistance with maximum power.
4. Operating temperature.

The photocurrent value is maximum in full sunlight (1.0 sun). On a partially sunny day, the photocurrent decreases in direct proportion to the intensity of the sun. The I-V curve shifts downward, resulting in a lower photocurrent generated by the sun. The figure below shows the relationship between intensity and voltage.

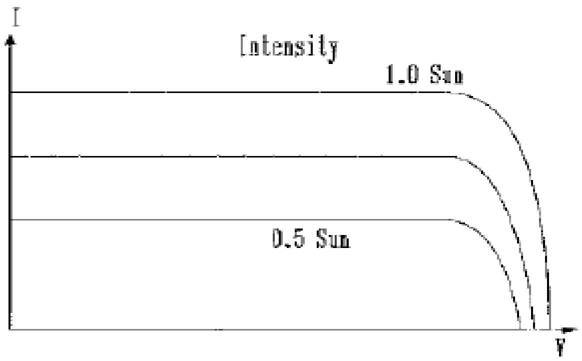

Figure 5 VAX at different intensities

On a cloudy day, the short-circuit current is significantly reduced and the drop in operating voltage is negligible. The photoconversion efficiency of the element is insensitive to solar radiation in the practical operating range.

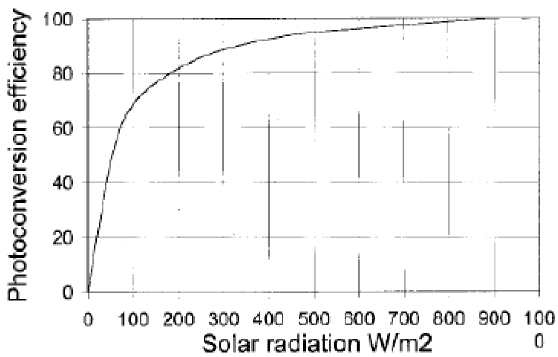

Figure 6. Photoconversion efficiency of the cell as a function of solar radiation

Figure 6 shows that the efficiency is almost the same at 500 W/m2 and 1000 W/m2. This means that the conversion efficiency is the same on a bright sunny day and a cloudy day. We simply produce less power on cloudy days because less solar energy is incident on the cell.

The output current of the cell is expressed as:

$$I = I_0 \cos\theta \quad (6)$$

Here I0 is the current generated by the sunlight incident on the photovoltaic cell and is the angle of the sun line measured from the normal. This law of cosines works well for sun angles from 0° to about 50°. Above 50°, the power output deviates significantly from the law of cosines, and the photovoltaic cell will not produce power after 85°, even though it should produce 7.5% of the energy according to the mathematical law of cosines. The dependence of the angle of the PV cell on the angle is called the Kelly cosine and can be seen in the figure and table below.

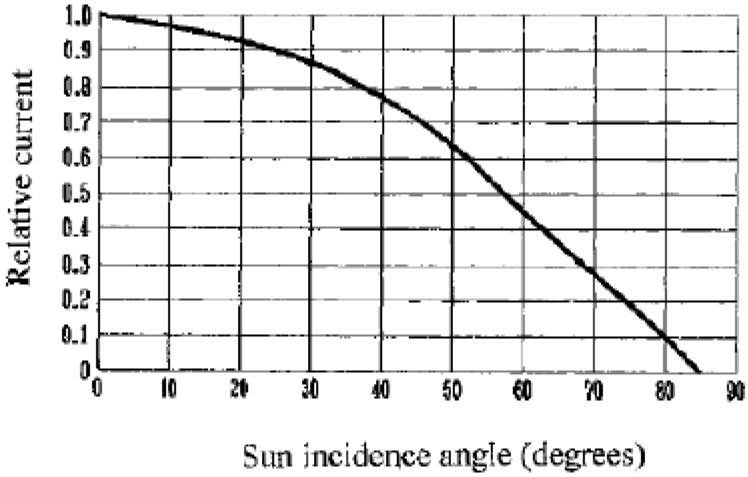

Figure 7. The dependence of the absorption of sunlight by a photovoltaic cell on the angle of incidence of sunlight

We can see the results obtained using Kelly's law in the following table:

solar angle degrees	*the mathematical cosine value*	*Kelly cosine value*
30	0.866	0.866
50	0.643	0.635
60	0.500	0.450
80	0.174	0.100
85	0.087	0

Table. Effect of Incidence Angle on Efficiency

Due to the structure that obstructs the direction of sunlight, if a photocell in a long string is completely shaded, it will lose voltage, but it must still carry current in the string because it is in series with other fully functioning photocells. Without an internally generated voltage, the photocell cannot produce power. Instead, it acts as a resistor and generates I2Rt loss or heat. The remaining photocells in the string must operate at a higher voltage to compensate for the voltage loss of the shaded photocell. The higher voltage in well-functioning photocells means that the cell will have a lower current draw than the I-V curve. This is shown in the lower left corner of Figure 48. The current loss is not proportional to the shaded area and may be negligible in small areas due to weak shading. However, if more photocells are shaded than a critical threshold, the I-V characteristic will be below the operating voltage of the cell, causing the cell current to drop to zero and the cell to lose all of its power.

To eliminate shadow loss, a common method is to divide the circuit into several segments, bypassing the diodes that cause the circuit to fail, as shown in Figure 49. The diode in the shadowed segment conducts only that segment of the photovoltaic cell. This results in a proportional loss of line voltage and current without losing the entire power of the cell. Some modern PV modules have such built-in conduction diodes.

Analysis. The operating point of any power system is the intersection of the source line and the resistance line. If the PV source has the I-V curve shown in Figure (a) and the resistor R1 supplies power, it operates at point a1.

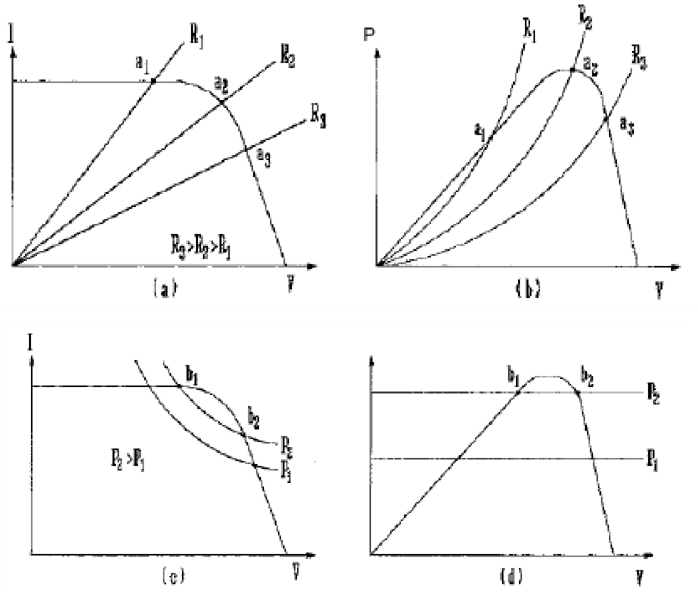

Figure 8 shows the operating points

If the resistance is increased to R_2 or R_3, the operating point shifts to a_2 or a_3 respectively. The maximum power is extracted from the resistive module when its resistance is R_2 (Figure b). Matching this load to the source is always necessary to maximize the power output from the PV module. Operation with constant power resistors is shown in Figures (c) and (d).

The constant power resistor line has two points where it intersects the source line, labeled B_1 and B_2. Only point B_2 is stable because it generates a renewable power to feed back any disturbance operation to B_2. Therefore, the system operates on B_2. The necessary condition for the electrical stability of a solar cell is as follows:

$$\left[\frac{dP}{dV}\right]_{load} \geq \left[\frac{dP}{dV}\right]_{source} \qquad (7)$$

Some consumers, such as heaters, have a constant resistance and the power varies with the resistance. On the other hand, some consumers, such as induction motors, act more like a constant power resistor, drawing more current at a lower voltage. In most large resistance systems, the power varies approximately linearly with the voltage. As the temperature increases, the short-circuit current of the element increases, while the voltage that causes the open circuit to break down decreases. The effect of temperature on the power is determined by the formula for examining the effect of current and voltage separately. Let Io and Uo be the short-circuit current and the open-circuit voltage at the reference temperature T, and a and b are their respective temperature coefficients. If the operating temperature is increased by ΔT, the new current and voltage are determined as follows:

$$I = I_0\left(1 + \alpha \Delta T\right) \qquad (8)$$

and

$$I = I_L - I_D\left[e^{\frac{QV_{OC}}{AKT}} - 1\right] - \frac{V_{OC}}{R_{SH}} \qquad (9)$$

Since the operating current and voltage change in approximately the same proportion as the short-circuit current and open-circuit voltage, respectively, the new power is:

$$P = I \cdot V = I_0(1+\alpha\Delta T)\cdot V_0(1-\beta\Delta T) \quad (10)$$

Ignoring the small term, this can be simplified to the following expression:

$$P = P_0 \cdot \left[1+(\alpha-\beta)\cdot\Delta T\right] \quad (11)$$

For typical monocrystalline silicon photovoltaic cells, the normal state is 500 and the normal state is 5. Thus, the power is:

$$P = P_0 \cdot \left[1+(500\mu u - 5mu)\cdot\Delta T\right] \text{ yoki } P = P_0 \cdot \left[1-0.0045\cdot\Delta T\right] \quad (12)$$

Since the increase in current is much smaller than the decrease in voltage, the net effect is a decrease in power at higher operating temperatures. This expression shows that for every 1°C increase in operating temperature above the normal temperature, the output power of a silicon photovoltaic cell decreases by 0.45%.

Conclusion. Thus, colder temperatures are better for a solar cell because they produce more power. However, the two maximum power Pmax do not correspond to the same voltage. To obtain maximum power at all temperatures, the PV system must be designed to increase the output voltage of the module to V2. Pmax2 must be maintained at a lower temperature, and at higher temperatures it must be reduced to V1 to obtain Pmax1. The data show that the short-circuit current of the solar cell increases almost linearly with increasing illumination intensity, while the open-circuit voltage changes relatively slowly. The maximum power point was determined from the current-voltage characteristics, and the filling factor was calculated based on it. According to the results obtained, it was determined that under optimal illumination conditions, the useful work coefficient of a silicon-based solar cell has a maximum value within a certain range. During the experiments, it was confirmed that the Edibon device has the ability to make high-precision measurements. An increase in the illumination intensity leads to an increase in electron-hole pairs, which increases the output current. At the same time, it was observed that an increase in temperature can cause a decrease in the open circuit voltage. The results obtained using the Edibon device allow students to explain the principle of operation of solar cells and their photoelectric properties through practical experiments. This is of great importance in training specialists in renewable energy sources. In this study, the main photoelectric parameters of silicon-based solar cells were experimentally determined using the Edibon device. The results obtained showed that the efficiency of solar cells directly depends on the illumination conditions.

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