MATHEMATICAL MODELING OF SOLAR PHOTOELECTRIC BATTERIES IN MATLAB/SIMULINK SYSTEM

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Abstract: this article presents the current situation and development prospects of the use of solar photovoltaic batteries in the world and in Uzbekistan, the analysis of scientific research conducted on the mathematical modeling of solar photovoltaic batteries, and the methodology for evaluating the overall efficiency of solar photovoltaic batteries in changing climate conditions. Mathematical model of KC200GT type solar module was built in MATLAB/Simulink system and results were obtained. The general efficiency indicators of solar photovoltaic batteries are presented as mathematical expressions depending on solar radiation, external temperature and the degree of dusting on the surface of solar photovoltaic batteries. The maximum output power of the solar photovoltaic cell is 200 W when the solar radiation is 1000 W/m ^{2} and the outdoor temperature is 25 ^{0} C, and the output power is 180, 165 and 148 W when the outdoor temperatures are 35, 45 and 55 ^{0} C, respectively. determined by the method. The output voltage of the solar module changes when the external temperature changes, and the output current changes when the solar radiation changes. When the amount of dust on the surface of solar photoelectric batteries is about 0.1 gr/m ^{2}, the efficiency of the device is maximum 16%, if the efficiency of the device is 80 gr/m ^{2}, it is found in experiments that it drops to 4%. Based on the results of the research, the importance of developing the use of energy-saving additional cooling and surface cleaning devices in increasing the efficiency of solar photovoltaic batteries in changing climate conditions is stated.

Keywords: solar photovoltaic cells, solar radiation, outdoor temperature, dust level, modeling, MATLAB/Simulink system, efficiency indicators.

The use of solar energy, in particular solar photovoltaic batteries, is developing in the energy system of the world. It can be seen that the global demand for electricity is increasing every year. If we take the last five years, the world's electricity demand is increasing by 50% every year. This requires the increase and development of alternative energy types. If we pay attention to the information of the International Energy Agency, if the use of solar energy develops at such a pace, by 2050 it will be possible to meet 25% of the world's electricity needs due to solar energy, and it will be possible to reduce the carbon dioxide gas released into the environment by 6 billion tons [1,2,3].

Global electricity generation from solar photovoltaic cells is set to reach a record 270 TW/h in 2022, a 26% increase over the previous year, to nearly 1,300 TW/h. It surpassed all renewable energy technologies in 2022, notably wind power for the first time in history. Continued growth in the economic attractiveness of solar photovoltaic cells, massive supply chain development, and increased policy support are expected to further accelerate capacity growth in the coming years, especially in China, the United States, the European Union, and India. According to the scientists' future predictions, the capacity of solar photovoltaic cells

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will almost triple by 2027, increasing the installed capacity by approximately 1,500 GW during this period, compared to the use of natural gas by 2026 and coal by 2027 [4].

In the Development Strategy of New Uzbekistan for 2022-2026, special attention is paid to the development of "green" energy in our country. In particular, renewable energy sources with a total capacity of 4,300 MW will be launched by the end of 2023 . This includes 2,100 MW large solar and wind power plants; 1,200 MW of solar panels installed in the social sector, farm buildings and structures, and apartments; 550 MW of small photoelectric plants built by entrepreneurs [5].

Special attention is paid to reliable assessment of changes in energy indicators of solar photovoltaic batteries in different climatic conditions (solar radiation, external temperature and wind speed changes), mathematical modeling and improvement of efficiency. Mathematical modeling of solar photovoltaic cells allows researchers to obtain high-accuracy results in research objects. In particular, software such as C++, Excel, MATLAB, Simulink, etc. differ depending on the methodology proposed by the researchers. Scientific research is being conducted on mathematical modeling of solar photoelectric batteries and improving their efficiency in different climatic conditions.

Mathematical modeling results of DS-100M solar photovoltaic battery in MATLAB/Simulink system by XH Nguyen and MP Nguyen are presented. Taking into account solar radiation and external temperature changes, the energy parameters of the device, i.e. changes in voltage, current and power, were evaluated. In this, changes in external temperature 25...75 ^{0} C and solar radiation 100...1000 W/m ^{2} were taken into account. According to the results of the study, it was found that the voltage and power of solar photovoltaic batteries decrease when the temperature exceeds the standard indicator, and the current decreases when the solar radiation decreases from normal [6].

F.M. Zaihidee and others presented the results of a scientific study on the effect of the dustiness of the surface of solar photovoltaic batteries on its energy parameters, which greatly affects the efficiency of solar photovoltaic batteries. The degree of degradation on the surface of solar cells is mainly based on the dependence of the deposition density, which is controlled by various factors. It has been found that 20g/m ^{2} dust accumulation of solar photovoltaic cells reduces the short-circuit current, voltage and efficiency by 15...21%, 2...6% and 15...35%, respectively [7].

M. Bayrakchi and others carried out scientific studies on the modeling of the temperature dependence of the capacity of solar photovoltaic batteries. This research focuses on the relationship between electricity production performance and changing temperature. Two models were developed to represent temperature effects on photovoltaic systems using Transient System Simulation (TRNSYS), a FORTRAN-based modular program for solar energy conversion and heat transfer estimation. Energy production differences for 236 US cities were used to create contour maps showing the surface of constant differences between these two models. Compared to Model B, power generation increases (16%-20%) for the Northeast and Midwest US regions in November-February, and slightly decreases from May to August (-4%). On the other hand, in the southern and southwestern part of the USA, energy production decreases significantly from May to August (- 12% - 15%), while it is found that it increases slightly from December to February (5%) [8].

The scientific research carried out above has not sufficiently addressed the issues of modeling the general efficiency indicators of solar photovoltaic batteries. In this case, it is important to develop a mathematical model to evaluate the changes in energy indicators of solar photovoltaic cells due to solar radiation, solar cell surface dusting, and external temperature changes.

The purpose of the research is to improve the mathematical model for evaluating solar photovoltaic cells solar radiation, dusting of the surface of solar photovoltaic cells and changes in external temperature depending on the efficiency of the device.

Equivalent circuit and mathematical expressions of the solar module. In order to use solar cells effectively, it is necessary to analyze the PV and IU characteristics of the solar module first. When analyzing PU and IU characteristics, we need to take into account solar radiation and temperatures. Figure 1 shows the equivalent circuit of a solar cell. This model represents the corresponding circuit diagram of the system and is called the "four-parameter model" consisting of "current source", "diode", "shunt" resistance and parallel resistance. A diode is connected in parallel with a current source that produces light, representing a theoretical model of an ideal solar cell. When sunlight hits the surface of the element, a direct current is generated that varies linearly with the solar radiation.

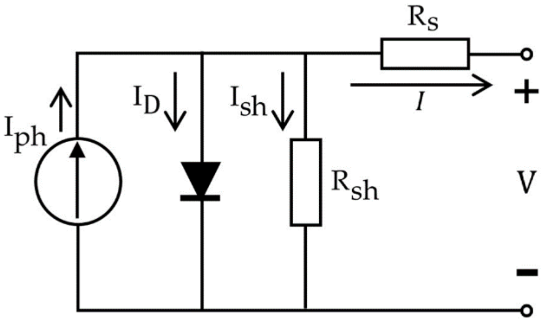


Figure 1. Equivalent circuit of a solar cell

The saturation current, reverse saturation current, current flowing through the shunt resistance, photocurrent, output current of the solar cell are determined by the following mathematical expressions [9,10,11]:

$$\begin{cases} I_0 = I_{rs} \cdot \left(\frac{T}{T_r}\right)^3 \cdot \exp\left[\frac{q \cdot E_{g0}}{n \cdot k} \cdot \left(\frac{1}{T} - \frac{1}{T_r}\right)\right] & (1) \\ I_{rs} = \frac{I_{sc}}{\exp\left(\frac{q \cdot Voc}{N_S \cdot k \cdot n \cdot T}\right) - 1} & (2) \\ I_{sh} = \frac{V + I \cdot R_S}{R_S} & (3) \\ I_{ph} = \frac{[I_{sc} + k_i \cdot (T - 298)] \cdot I_r}{1000} & (4) \\ I = I_{ph} - I_0 \cdot \left[\exp\left\{(V + R_s) \cdot \frac{q}{n \cdot k \cdot T \cdot N_s}\right\} - 1\right] - I_{sh} & (5) \end{cases}$$

These expressions reflect the relationship between the voltage and current of the solar module. Let's find out what the parameters in the expressions are: N_s —the number of elements in the solar module;R_s and R_{sh}series and shunt resistances of the solar cell; q —the charge of an electron, $1{,}6 \cdot 10^{-19}$C; k —Bolsman constant, $1{,}38 \cdot 10^{-23}$J/K; V —output voltage; T —working temperature, T_r —nominal temperature; V_{oc} —operating voltage only; n —ideality coefficient of the diode; E_{g0} —band gap energy of a semiconductor; k_i —short circuit current (25 ^{0}C, 1000 W/m ^{2}); I_{sc} —short circuit current.

The reliable operation of solar photovoltaic cells mainly depends on the solar radiation and the external temperature, and the maximum efficiency of the solar modules is when the nominal temperature is 25 ^{0}C. We give theoretical calculations of the efficiency of operation of solar photoelectric batteries at different temperature regimes. The dependence of the power of solar photovoltaic batteries on the external temperature is determined by the following mathematical expression [12]:

$P = P_{sts} + P_{T-coeff} \cdot (T_c - T_{NOCT})(6)$

where: P_{sts} —power of the solar photovoltaic battery , W;$P_{T-coeff}$ – specific power factor depending on temperature, 0.004 W/ ^{0}C (200 W, -0.8 W/ ^{0}C); T_c —outside temperature ^{0}C; T_{NOCT} —nominal temperature in the solar module, 25 ^{0}C.

The dependence of the efficiency of solar photoelectric batteries on the external temperature is determined by the following mathematical expression [13]:

$\eta = \eta_P \cdot (1 - \beta \cdot (T_c - T_{NOCT}))$ (7)

where: solar module η_P —efficiency β —in nominal mode (1000 W/m ^{2}, 25 ^{0}C) ; power variation temperature coefficient, 0.004 W/ ^{0}C.

The empirical equation of the dependence of the amount of dust on the surface of solar photovoltaic cells on the efficiency indicator is as follows [14]:

$\eta = 12{,}3 \cdot \exp\left(-\frac{\rho}{17{,}4}\right) + 4{,}2(8)$

where: ρ —relative dust content, gr/m ^{2}.

In Figure 2, the dependence of the saturation current of the solar cell on the temperature change and the parameters of the solar cell is built in the MATLAB/Simulink system by the expression (1) model is presented.

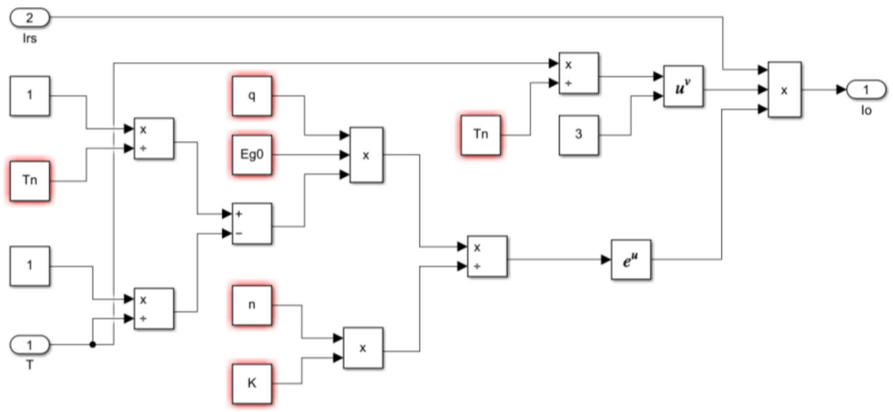


Figure 2. Solar cell saturation current model

In Figure 3, the dependence of the reverse saturation current of the solar cell on the parameters of the solar cell, that is, the number of cells in the solar module, the short-circuit current, and the operating voltage is constructed by the expression (2) in the MATLAB/Simulink system model is presented.

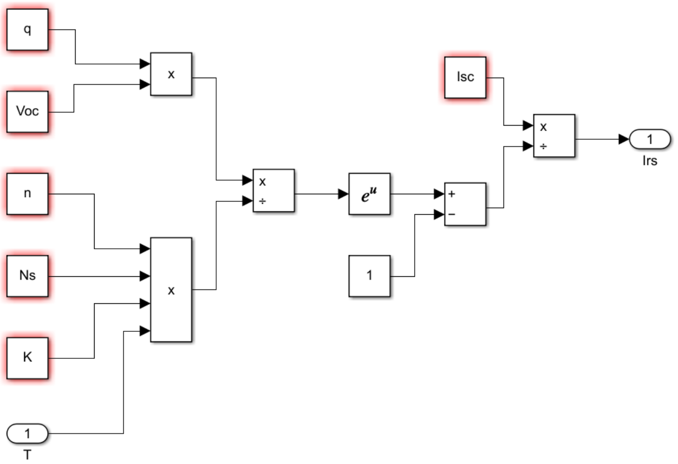


Figure 3. Solar cell reverse saturation current model

In Figure 4, the dependence of the solar cell current in the shunt resistance on the parameters of the solar cell, i.e., the output voltage and the resistors connected in series, is built in the MATLAB/Simulink system by expression (3) model is presented.

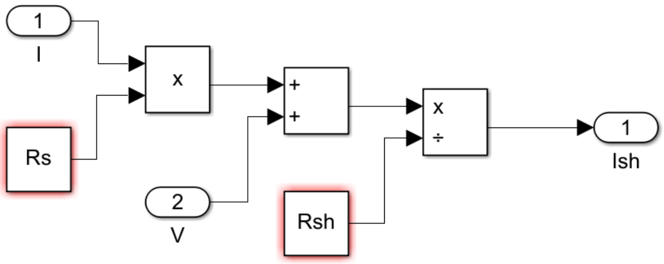


Figure 4. Current model of solar cell in shunt resistance

In Figure 5, the dependence of the solar cell photocurrent on solar radiation and temperature changes, on the parameters of the solar cell, that is, on the short-circuit current, is built in the MATLAB/Simulink system by expression (4) model is presented.

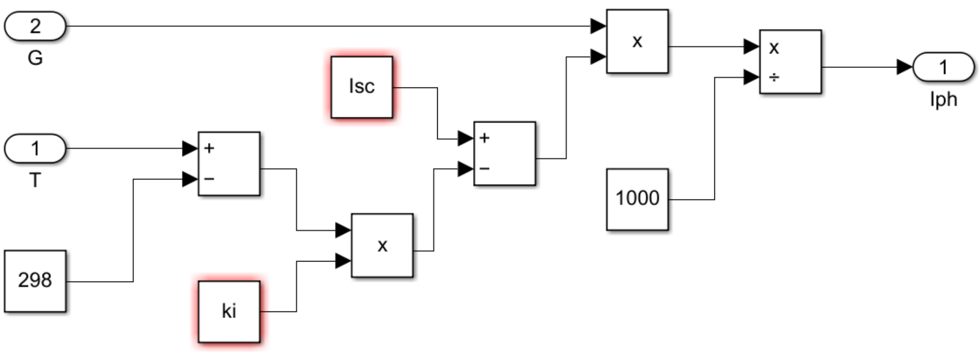


Figure 5. Photo current model of Q cell

Figure 6 shows the dependence of the output current of the solar cell on the external temperature change, saturation current, current flowing through the shunt resistance, photocurrent and parameters of the solar cell by expression (5) built in the MATLAB/Simulink system model is presented.

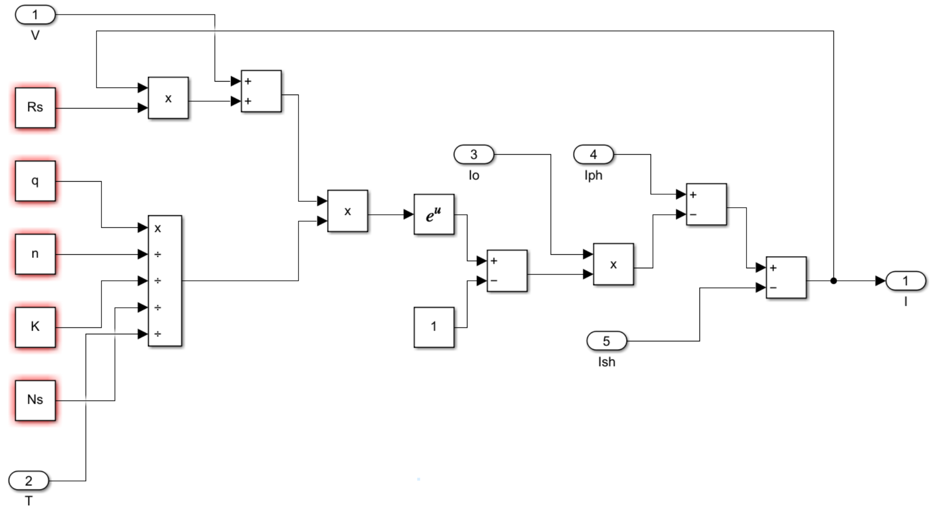


Figure 6. Solar cell output current model

Figure 7 shows the model of the solar module in the MATLAB/Simulink system. The input parameters are solar radiation and external temperature, and the output parameters are voltage and current modeling block diagrams.

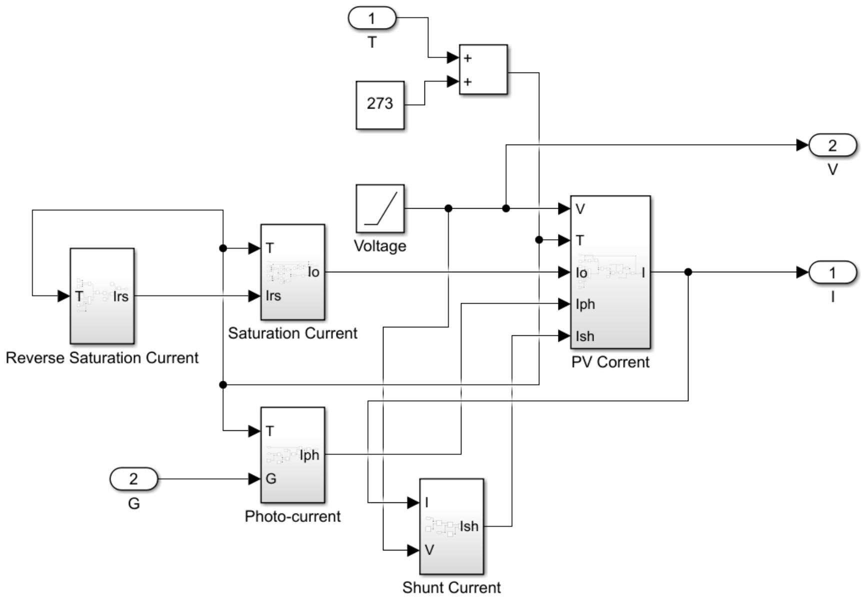


Figure 7. MATLAB/Simulink model of solar module

Figure 8 shows a simplified block diagram of the solar module in MATLAB/Simulink. It presents a model capable of obtaining IV, PV characteristics when solar radiation and external temperature change.

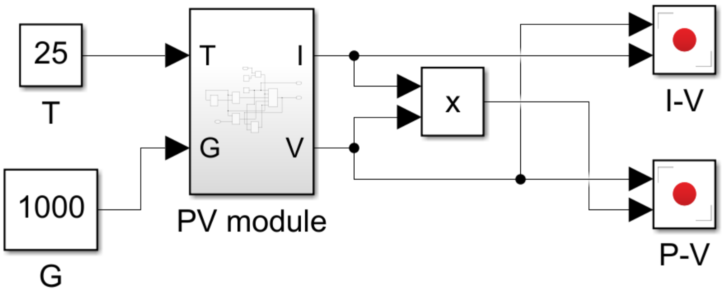


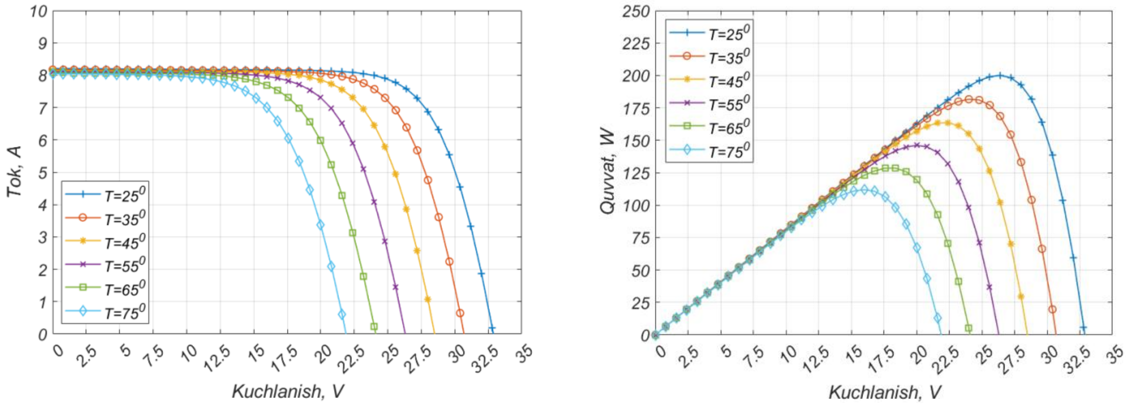
Figure 8. A simplified block diagram of the solar module in MATLAB/Simulink

Table 1 lists the parameters of the KC200GT solar module. We use these energy parameters in modeling solar photovoltaic cells.

Table 1

Model	KC200GT
Element type	Polycrystalline silicon 156x156 mm
Maximum power, P [W]	200
Salt operating voltage, V_{oc}[V]	32.9
Short circuit current, I_{sc}[A]	8.21
Voltage at maximum power, U_{mp}[V]	26.3
Current at maximum power, I_{mp}[A]	7.61
K_V[V/C]	-0.1230
K_I[A/C]	0.0032
a	1.3
R_{sh}[Ω]	415,405
R_s[Ω]	0.221
N $_s$	54

Figure 9 shows the curves of solar module output current versus voltage (a) and power versus voltage (b) when the solar radiation is 1000 W/m ^{2} . It was found that when the temperature increases, the output voltage and power of the solar module decreases. When the external temperature is 25 ^{0} C and the solar radiation is 1000 W/m ^{2} , the maximum output power is 200 W, and when the temperature is 75 ^{0} C, the output power is approximately 110 W.

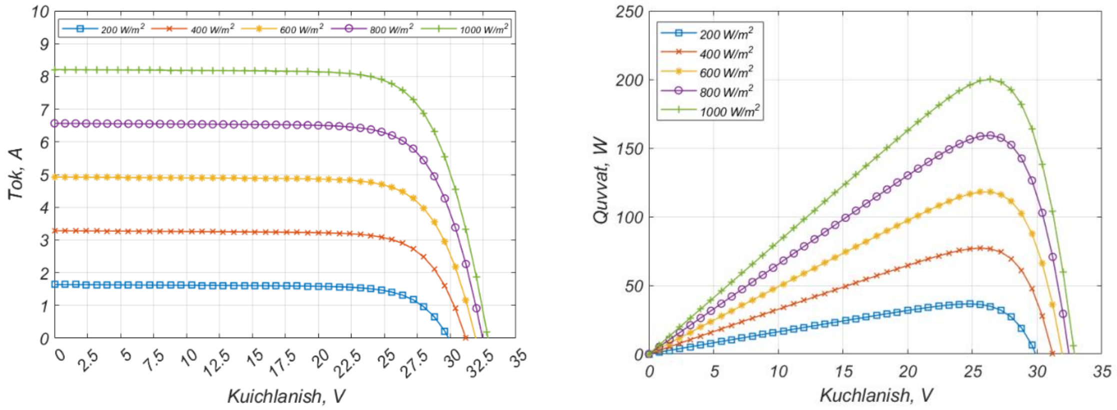


a) b)

Figure 9. Solar module output current versus voltage (a) and power versus voltage (b) curves of external temperature change

Figure 10 shows the dependence curves of the solar module output current on voltage (a) and power on voltage (b) of solar radiation change when the external temperature is 25 ^{0} C. It was found that when the solar radiation decreases, the output current and power of the solar module decreases. When the solar radiation is 1000 W/m ^{2} and the temperature is 25 ^{0}

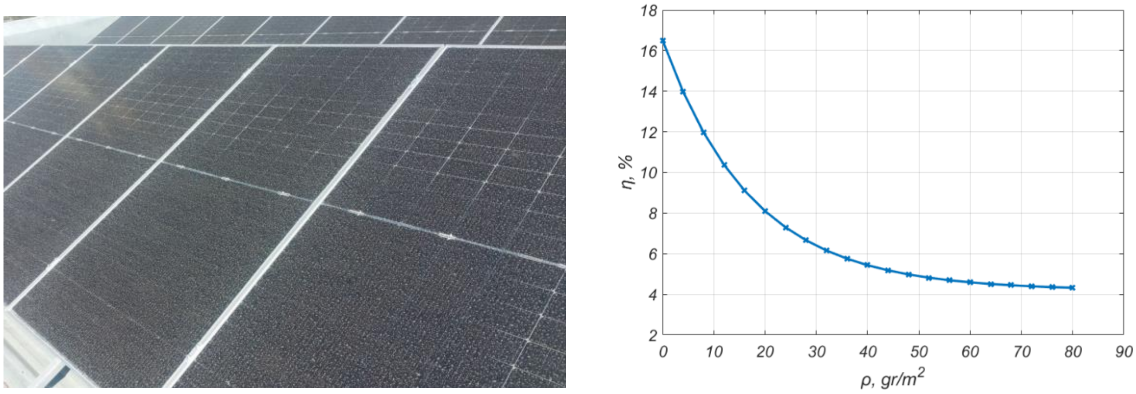
C, the maximum output power is 200 W, and when the solar radiation is 200 W/m ^{2} , the output power is approximately 48 W.



a) b)

Figure 9. Curves of dependence of solar radiation change of solar module output current on voltage (a) and power on voltage (b)

Figure 10 shows the curve of the dependence of the amount of dust (a) on the surface of the solar photovoltaic cell (b) and its efficiency. In this case, when the amount of dust on the surface of solar photoelectric batteries is about 0.1 gr/m ^{2} , the efficiency of the device is maximum 16%, if the efficiency of the device is 80 gr/m ^{2} , it was found in the experiments to decrease to 4%. Empirical equation (8) was used to determine these results.



a) b)

Figure 10. The state of dusting of the solar photoelectric battery (a) and the dependence curve of the amount of dusting on the efficiency of the device (b)

Based on the results of the research, it is important to develop the use of energy-saving additional cooling and surface cleaning devices in increasing the efficiency of solar photovoltaic batteries in changing climate conditions.

Conclusion. Analyzes of the current state of use of solar photoelectric batteries in the world and in Uzbekistan and development prospects were presented. It is noted that by 2050, 25% of the world's electricity needs can be met by solar energy and that carbon dioxide emissions will be reduced by 6 billion tons per year;

Mathematical model of KC200GT type solar module was built in MATLAB/Simulink system and results were obtained. The general efficiency indicators of solar photovoltaic

batteries are presented as mathematical expressions depending on solar radiation, external temperature and the degree of dusting on the surface of solar photovoltaic batteries. When the solar radiation is 1000 W/m ^{2} and the outdoor temperature is 25 ^{0} C, the maximum solar photovoltaic cell is 200 W, when the outdoor temperatures are 35, 45, and 55 ^{0} C, the output power is 180, 165, and 148 W, respectively. determined by the method;
the amount of dust on the surface of solar photoelectric batteries is about 0.1 gr/m ^{2} , the efficiency of the device is maximum 16%, if the efficiency of the device is 80 gr/m ^{2}, it is found in experiments that it drops to 4%.

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