

Mathematical Modeling Of Solar Photovoltaic Panels In The Matlab/Simulink Environment

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Abstract: The paper presents the current state and development prospects of the use of solar photovoltaic (PV) panels in the world and in Uzbekistan, an analysis of scientific research on the mathematical modeling of solar PV panels, and a methodology for assessing the overall efficiency of solar PV panels under variable climatic conditions. A mathematical model of the KC200GT solar module was built in the Matlab/Simulink environment and the results were obtained. Mathematical expressions are given for the dependence of the overall efficiency indicators of solar PV panels on solar radiation, ambient temperature, and the degree of dust accumulation on the surface of the panels. It was determined by the modeling method that at a solar radiation of 1000 W/m^2 and an ambient temperature of 25°C the solar PV panel delivers a maximum of 200 W , and at ambient temperatures of 35 , 45 , and 55°C the output power is 180 , 165 , and 148 W , respectively. The change in the output voltage of the solar module with ambient temperature and the change in the output current with solar radiation were studied. It was determined in experiments that at a dust accumulation of approximately 0.1 g/m^2 on the surface of the solar PV panels the maximum efficiency of the device is 16% , while at 80 g/m^2 the efficiency decreases to 4% . Based on the research results, the importance of developing energy-saving auxiliary cooling and surface-cleaning devices to increase the efficiency of solar PV panels under variable climatic conditions is stated.

Keywords: Solar photovoltaic panels, solar radiation, ambient temperature, dust accumulation level, modelin, Matlab/Simulink environment, efficiency indicators.

The use of solar energy, in particular solar photovoltaic panels, is developing in the world's energy system. It can be seen that the demand for electricity worldwide is increasing from year to year. Over the last five years, the global demand for electricity has been growing by 50% every year. This calls for expanding and developing alternative energy sources. According to the International Energy Agency, if the use of solar energy continues to develop at this pace, by 2050 it will be possible to meet 25% of the world's electricity demand with solar energy and to reduce annual carbon dioxide emissions into the environment by 6 billion tons [1,2,3].

Worldwide, electricity generation from solar PV panels reached a record 270 TWh in 2022, an increase of 26% over the previous year, reaching almost 1300 TWh . In 2022 this surpassed all other renewable energy technologies and, for the first time in history, wind power. The continuous growth in the economic attractiveness of solar PV panels, the large-scale development of the supply chain, and stronger policy support are expected to accelerate capacity growth further in the coming years, especially in China, the USA, the European Union, and India. According to scientists' forecasts, by 2027 the capacity of solar PV panels will almost triple, with installed capacity growing by about 1500 GW over this period, and will exceed natural gas by 2026 and coal by 2027 [4].

In the Development Strategy of New Uzbekistan for 2022–2026, special attention is also paid to the development of “green” energy in our country. In particular, renewable energy sources with a total capacity of $4,300 \text{ MW}$ will be commissioned by the end of 2023. These include $2,100 \text{ MW}$ of large solar and wind power plants; $1,200 \text{ MW}$ of solar panels to be installed on social facilities, commercial buildings and structures, and households; and 550 MW of small photovoltaic plants to be built by entrepreneurs [5].

Special attention is being paid to the reliable assessment of changes in the energy performance of solar PV panels under various climatic conditions (changes in solar radiation, ambient temperature, and wind speed), to mathematical modeling, and to increasing their efficiency. Mathematical modeling of solar PV panels allows researchers to obtain highly accurate results for the objects under study. In particular, the models differ depending on the software used, such as C++, Excel, Matlab, and Simulink, and on the methodologies proposed by researchers. Scientific research on the mathematical modeling of solar PV panels and on improving their efficiency under various climatic conditions is being carried out.

X.H. Nguyen and M.P. Nguyen presented the results of mathematical modeling of the DS-100M solar PV panel in the Matlab/Simulink environment. Taking into account changes in solar radiation and ambient temperature, the changes in the energy parameters of the device, namely voltage, current, and power, were assessed. Ambient temperatures of 25...75 °C and solar radiation of 100...1000 W/m² were considered. According to the research results, it was found that when the temperature exceeds the normal value, the voltage and power of solar PV panels decrease, and when solar radiation falls below normal, the current decreases [6]. F.M. Zaihidee et al. presented research results on the effect of the dust accumulation level on the surface of solar PV panels, a factor that strongly affects their efficiency, on their energy parameters. The degree of degradation of the surface of solar panels is based mainly on the deposit density, which is governed by various factors. It was found that dust accumulation of 20 g/m² on solar PV panels reduces the short-circuit current, voltage, and efficiency by 15...21%, 2...6%, and 15...35%, respectively [7].

M. Bayrakci et al. carried out research on modeling the temperature dependence of the power of solar PV panels. This study focused on the relationship between electricity generation indicators and varying temperature. Two models were developed to show the effect of temperature on photovoltaic systems using Transient System Simulation (TRNSYS), a FORTRAN-based modular program for evaluating solar energy conversion and heat transfer. Differences in energy production for 236 cities in the USA were used to create contour maps showing the surface of persistent differences between these two models. Compared with Model B, power generation increases in November–February (16%–20%) and decreases slightly from May to August (–4%) in the northeastern and midwestern regions of the USA. On the other hand, it was found that in the south and southwest of the USA energy production decreases significantly from May to August (–12% to –15%) and increases slightly from December to February (5%) [8].

In the above research, the issues of modeling the overall efficiency indicators of solar PV panels have not been sufficiently addressed. In this regard, it is important to develop a mathematical model for assessing changes in the energy performance of solar PV panels as a function of solar radiation, dust accumulation on the surface of the panels, and variations in ambient temperature.

Aim of the research: to improve the mathematical model for assessing the dependence of solar PV panel efficiency on solar radiation, surface dust accumulation of solar PV panels, and changes in ambient temperature.

Equivalent circuit of the solar module and mathematical expressions. For efficient use of solar panels, first of all it is necessary to analyze the P–V and I–V characteristics of the solar module. When analyzing the P–V and I–V characteristics, it is necessary to take solar radiation and temperature into account. Fig. 1 shows the equivalent circuit of a solar cell. This model represents the corresponding electrical circuit of the system and is called the “four-parameter model,” consisting of a “current source,” a “diode,” a “shunt” resistance, and a parallel resistance. The light-generating current source, connected in parallel with the diode, represents the theoretical model of an ideal solar cell. When sunlight falls on the cell surface, it produces a direct current that varies linearly with the sunlight.

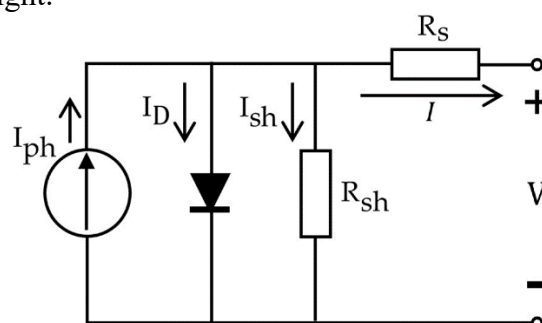


Fig. 1. Equivalent circuit of the solar cell

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

$$I_0 = I_{rs} \cdot \left(\frac{T}{T_r}\right)^3 \cdot \exp \left[\frac{q \cdot E_{g0}}{n \cdot k} \cdot \left(\frac{1}{T} - \frac{1}{T_r}\right) \right] \quad (1)$$

$$I_{rs} = \frac{I_{sc}}{\exp \left(\frac{q \cdot V_{oc}}{N_s \cdot k \cdot n \cdot T} \right) - 1} \quad (2)$$

$$I_{sh} = \frac{V + I \cdot R_s}{R_s} \quad (3)$$

$$I_{ph} = \frac{[I_{sc} + k_i \cdot (T - 298)] \cdot I_r}{1000} \quad (4)$$

$$I = I_{ph} - I_0 \cdot \left[\exp \left\{ (V + R_s) \cdot \frac{q}{n \cdot k \cdot T \cdot N_s} \right\} - 1 \right] - I_{sh} \quad (5)$$

These expressions reflect the relationship between the voltage and current of the solar module. The parameters used in the expressions are as follows: N_s – number of cells in the solar module; R_s and R_{sh} series and shunt resistances of the solar cell; q – electron charge, $1.6 \cdot 10^{-19}$ C; k – Boltzmann constant, $1.38 \cdot 10^{-23}$ J/K; V – output voltage; T – operating temperature, T_r – nominal temperature; V_{oc} – open-circuit voltage; n – diode ideality factor; E_{g0} – band-gap energy of the semiconductor; k_i – short-circuit current (25 °C, 1000 W/m²); I_{sc} – short-circuit current.

The reliable operation of solar PV panels depends mainly on solar radiation and ambient temperature, and the operating efficiency of solar modules is highest at a nominal temperature of 25 °C. Let us present theoretical calculations of the operating efficiency of solar PV panels at different temperature regimes. The dependence of the power of solar PV panels on ambient temperature is determined by the following mathematical expression [12]:

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

where: P_{sts} – power of the solar PV panel, W; $P_{T-coeff}$ – temperature-dependent specific power coefficient, 0.004 W/°C (200 W, -0.8 W/°C); T_c – ambient temperature, °C; T_{NOCT} – nominal temperature of the solar module, 25 °C.

The dependence of the efficiency of solar PV panels on ambient temperature is determined by the following mathematical expression [13]:

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

where: η_p – efficiency of the solar module at nominal conditions (1000 W/m², 25 °C); β – temperature coefficient of the power variation, 0.004 W/°C.

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

$$\eta = 12.3 \cdot \exp \left(-\frac{\rho}{17.4} \right) + 4.2 \quad (8)$$

where: ρ – specific dust accumulation, g/m².

Fig. 2 shows the model, built in the Matlab/Simulink environment according to expression (1), of the dependence of the saturation current of the solar cell on temperature changes and on the solar cell parameters.

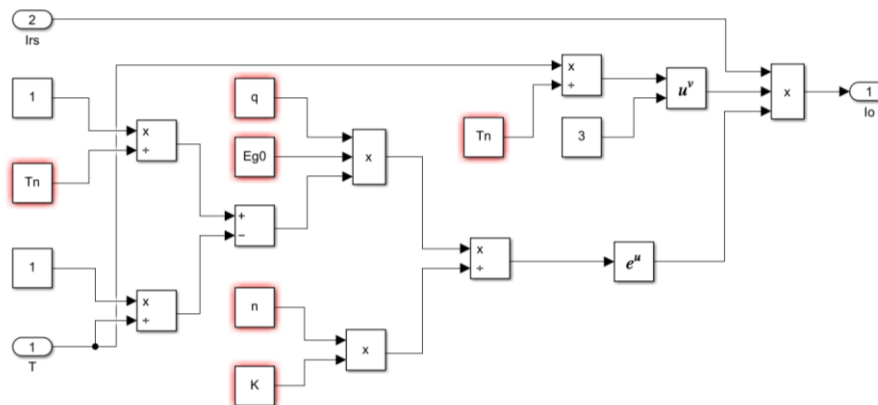


Fig. 2. Saturation current model of the solar cell

Fig. 3 shows the model, built in the Matlab/Simulink environment according to expression (2), of the dependence of the reverse saturation current of the solar cell on the solar cell parameters, namely the number of cells in the solar module, the short-circuit current, and the open-circuit voltage.

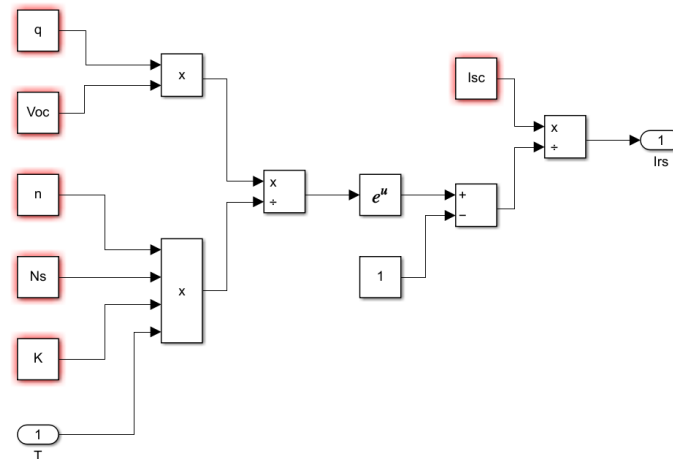


Fig. 3. Reverse saturation current model of the solar cell

Fig. 4 shows the model, built in the Matlab/Simulink environment according to expression (3), of the dependence of the current through the shunt resistance of the solar cell on the solar cell parameters, namely the output voltage and the series-connected resistances.

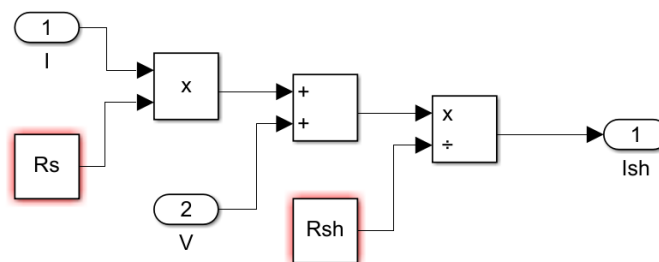


Fig. 4. Model of the current through the shunt resistance of the solar cell

Fig. 5 shows the model, built in the Matlab/Simulink environment according to expression (4), of the dependence of the photocurrent of the solar cell on changes in solar radiation and temperature and on the solar cell parameters, namely the short-circuit current.

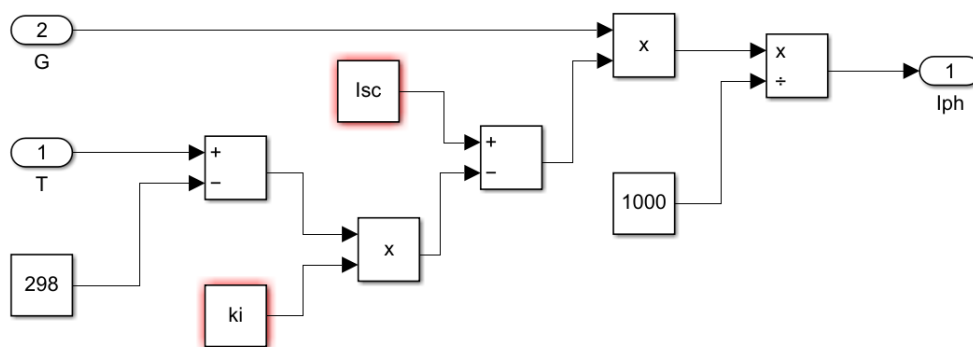


Fig. 5. Photocurrent model of the solar cell

Fig. 6 shows the model, built in the Matlab/Simulink environment according to expression (5), of the dependence of the output current of the solar cell on changes in ambient temperature, the saturation current, the current through the shunt resistance, the photocurrent, and the solar cell parameters.

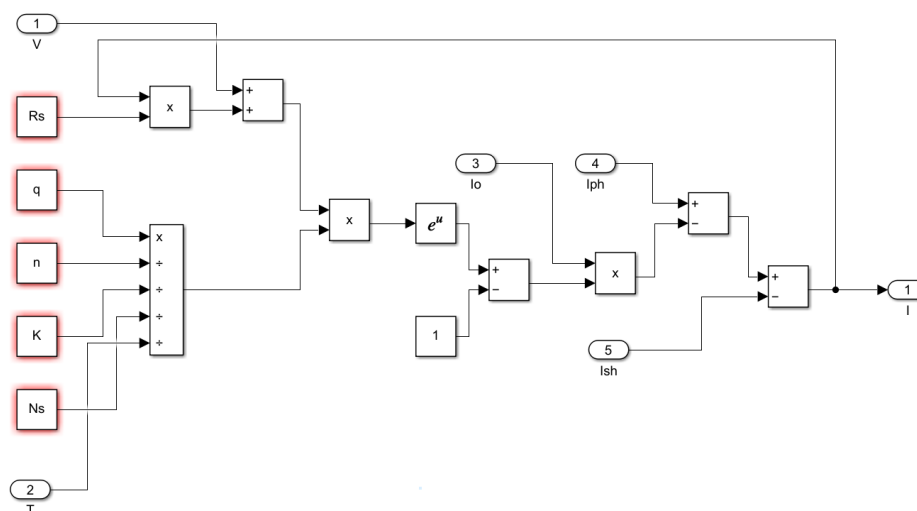


Fig. 6. Output current model of the solar cell

Fig. 7 shows the model of the solar module in the Matlab/Simulink environment. Block diagrams have been built for modeling, with solar radiation and ambient temperature as input parameters and voltage and current as output parameters.

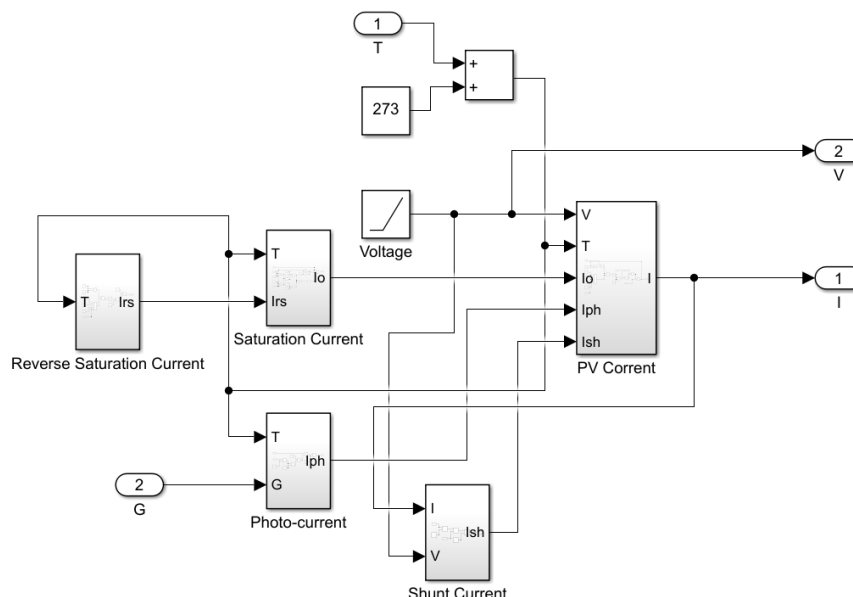


Fig. 7. Model of the solar module in the Matlab/Simulink environment

Fig. 8 shows a simplified block diagram of the solar module in the Matlab/Simulink environment. It presents a model that makes it possible to obtain the I-V and P-V characteristics when solar radiation and ambient temperature change.

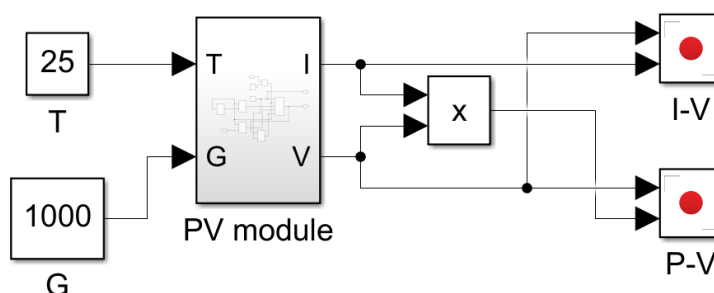


Fig. 8. Simplified block diagram of the solar module in the Matlab/Simulink environment

Table 1 presents the parameters of the KC200GT solar module. We use these energy parameters in modeling solar PV panels.

Table 1

Model	KC200GT
Cell type	Polycrystalline silicon 156×156 mm
Maximum power, P [W]	200
Open-circuit 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/K]	-0.1230
K_I [A/K]	0.0032
a	1.3
R_{sh} [Ω]	415.405
R_s [Ω]	0.221
N_s	54

Fig. 9 shows the curves of the dependence of the output current of the solar module on voltage (a) and of power on voltage (b) as the ambient temperature changes at a solar radiation of 1000 W/m². It was found that as temperature increases, the output voltage and power of the solar module decrease. At an ambient temperature of 25 °C and a solar radiation of 1000 W/m², the maximum output power is 200 W, and at a temperature of 75 °C the output power is approximately 110 W.

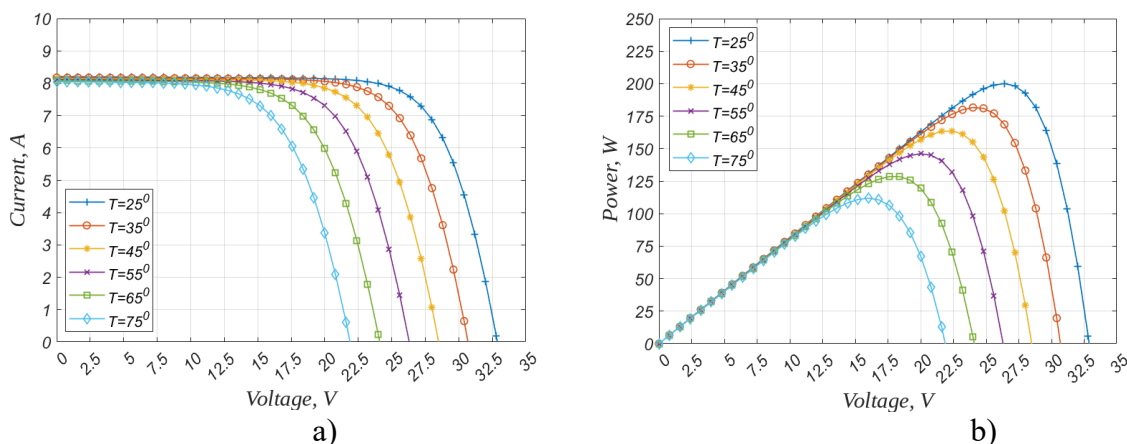


Fig. 9. Curves of the dependence of the output current of the solar module on voltage (a) and of power on voltage (b) as the ambient temperature changes

Fig. 10 shows the curves of the dependence of the output current of the solar module on voltage (a) and of power on voltage (b) as solar radiation changes at an ambient temperature of 25 °C. It was found that as solar radiation decreases, the output current and power of the solar module decrease. At a solar radiation of 1000 W/m² and a temperature of 25 °C, the maximum output power is 200 W, and at a solar radiation of 200 W/m² the output power is approximately 48 W.

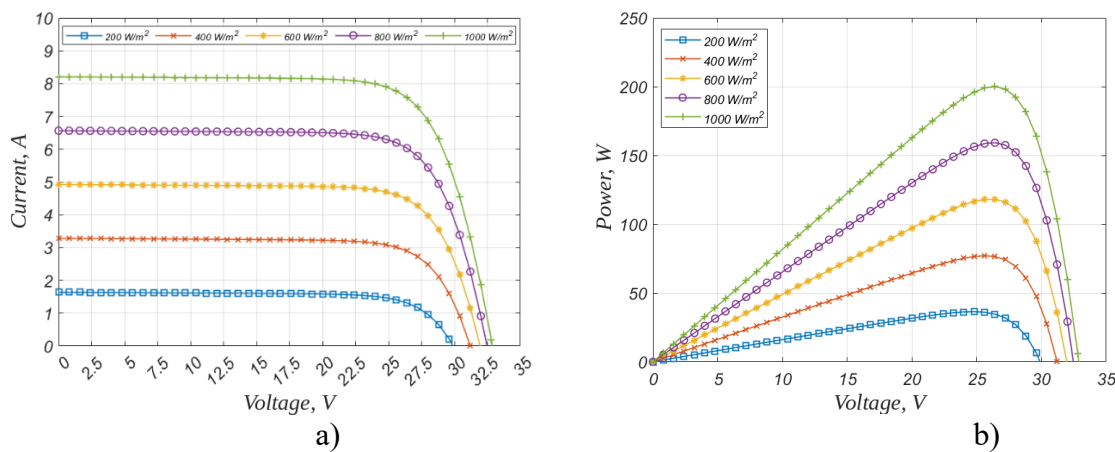


Fig. 10. Curves of the dependence of the output current of the solar module on voltage (a) and of power on voltage (b) as solar radiation changes

Fig. 11 shows the curve of the dependence of the efficiency of the solar PV panel on the amount of dust on its surface. It was determined in experiments that at a dust accumulation of approximately 0.1 g/m^2 on the surface of the solar PV panels the maximum efficiency of the device is 16%, while at 80 g/m^2 the efficiency decreases to 4%. The empirical equation (8) was used to determine these results.

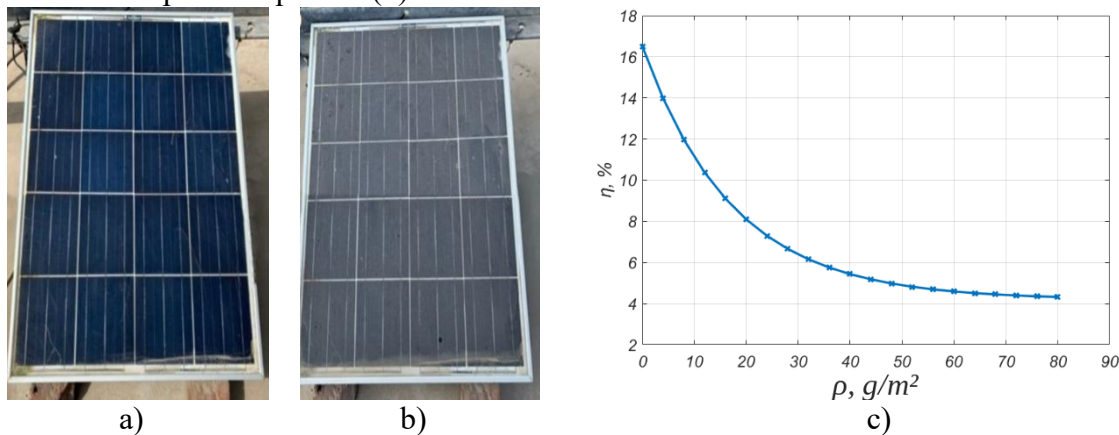


Fig. 11. Clean (a) and dusty (b) solar PV panel, and the curve of the dependence of the device efficiency on the amount of dust accumulation (c)

Based on the research results, the development of energy-saving auxiliary cooling and surface-cleaning devices is of great importance for increasing the efficiency of solar PV panels under variable climatic conditions.

Conclusion: An analysis of the current state and development prospects of the use of solar PV panels in the world and in Uzbekistan is presented. It is emphasized that by 2050 it will be possible to meet 25% of the world's electricity demand with solar energy and to reduce annual carbon dioxide emissions into the environment by 6 billion tons;

A mathematical model of the KC200GT solar module was built in the Matlab/Simulink environment and the results were obtained. Mathematical expressions are given for the dependence of the overall efficiency indicators of solar PV panels on solar radiation, ambient temperature, and the degree of dust accumulation on the surface of the panels. It was determined by the modeling method that at a solar radiation of 1000 W/m^2 and an ambient temperature of 25°C the solar PV panel delivers a maximum of 200 W, and at ambient temperatures of 35, 45, and 55°C the output power is 180, 165, and 148 W, respectively;

It was determined in experiments that at a dust accumulation of approximately 0.1 g/m^2 on the surface of the solar PV panels the maximum efficiency of the device is 16%, while at 80 g/m^2 the efficiency decreases to 4%.

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