INVESTIGATION OF FACTORS AFFECTING THE EFFICIENCY OF SOLAR PHOTOVOLTAIC PANELS

Kakhkhorov M.M.

The utilization of solar energy—particularly through solar photovoltaic (PV) panels—is rapidly expanding within global energy systems. Worldwide demand for electricity continues to rise significantly year after year. Over the past five years alone, global electricity demand has increased by approximately 50%, underscoring the urgent need to expand and develop alternative energy sources. According to data from the International Renewable Energy Agency (IRENA), if the current growth trajectory of solar energy adoption persists, solar power could meet 25% of global electricity demand by 2050 and reduce annual carbon dioxide emissions by 6 billion tons [1–3].

In 2022, global electricity generation from solar PV panels reached a record 1,300 TW·h — representing a 26% increase compared to the previous year's 270 TW·h. Notably, for the first time in history, solar PV surpassed wind energy among all renewable energy technologies in terms of annual capacity additions. The sustained economic attractiveness of solar PV systems, coupled with robust supply chain development and strengthened policy support—especially in China, the United States, the European Union, and India—is expected to further accelerate capacity growth in the coming years. Experts project that installed solar PV capacity will nearly triple by 2027, reaching approximately 1,500 GW. By 2026, solar PV generation is anticipated to exceed that from natural gas, and by 2027, it is expected to surpass coal-based generation [4].

Uzbekistan's Development Strategy for 2022–2026 places special emphasis on advancing "green" energy. Specifically, by the end of 2023, the country aims to commission 4,300 MW of renewable energy capacity, comprising:

- 2,100 MW from large-scale solar and wind power plants;
- 1,200 MW from solar panels installed on public facilities, residential buildings, and households;
- 550 MW from small-scale PV stations developed by private entrepreneurs [5].

The efficiency of solar photovoltaic panels is defined as the ratio of the total electrical energy produced by the system over a given period (e.g., kWh/year) to the total solar irradiance incident on the same area during that period (also expressed in equivalent kWh/year). This efficiency depends on several environmental factors—including solar irradiance, ambient temperature, wind speed, relative humidity, and atmospheric pressure—as well as intrinsic characteristics of the PV module itself, such as its rated power and operating temperature.

Solar Irradiance (W/m²): The amount of solar energy incident per unit area over a specific time interval. Electrical output from PV panels is directly proportional to solar irradiance; higher irradiance levels lead to greater power generation.

Ambient Temperature (°C): Ambient air temperature significantly influences PV performance, as solar cells are sensitive to thermal variations. An increase in module temperature typically results in reduced energy conversion efficiency.

Wind Speed (m/s): Wind enhances convective heat transfer from the panel surface, thereby lowering the operating temperature of PV modules. Higher wind speeds can improve system performance by mitigating thermal losses—particularly critical in hot climates. For optimal efficiency in such regions, panels should be mounted several centimeters above rooftops or ground surfaces to ensure continuous airflow and prevent overheating.

Relative Humidity (g/m³): While humidity does not directly affect electrical output, high moisture levels can promote dust adhesion and accumulation of particulate matter on panel surfaces. This soiling effect reduces light transmittance and, consequently, overall system efficiency.

Atmospheric Pressure (Pa): Although atmospheric pressure has no direct impact on electrical performance, significant pressure fluctuations—such as those associated with extreme weather events—can induce mechanical stress and compromise the structural integrity of PV modules, potentially affecting long-term reliability.

Module Rated Power (kW): This denotes the maximum electrical power a PV module can deliver under Standard Test Conditions (STC), typically expressed in watts (W) or kilowatts (kW).

Module Operating Temperature (°C): The actual temperature of the PV module during operation, influenced by solar irradiance, ambient temperature, wind speed, and heat dissipation mechanisms. Monitoring and controlling module temperature are crucial for optimizing performance, as elevated temperatures reduce output power and accelerate module degradation.

Research Objective: To investigate external factors influencing the efficiency of solar photovoltaic panels.

Reliable operation of solar PV systems primarily depends on solar irradiance and ambient temperature. Maximum efficiency is achieved at the standard module temperature of 25°C. Theoretical analyses of PV performance under varying thermal conditions are presented below.

The dependence of PV output power on ambient temperature is described by the following equation [6]:

$$P = P_0 \cdot [1 - \beta \cdot (T_a - T_0)] \ (1)$$

Where:

P – output power of the solar panel (W);

P_0 – rated power at standard conditions;

B – temperature coefficient of power (e.g., 0.004 W/°C for a 200 W panel, equivalent to –0.8 W/°C);

T_a – ambient temperature (°C);

T_0 – nominal module temperature (25°C).

Similarly, the relationship between the panel's efficiency (η) and ambient temperature is given by [7,8]:

$$\eta = \eta_0 \cdot [1 - \beta \cdot (T_a - T_0)] \ (2)$$

where η_0 is the nominal efficiency under STC (1000 W/m², 25°C).

The empirical relationship between dust accumulation on the panel surface and efficiency loss is expressed as [9]:

$$\eta = \eta_0 \cdot e^{-k \cdot d} \ (3)$$

where:

d – dust deposition density (g/m²);

k – empirical soiling coefficient.

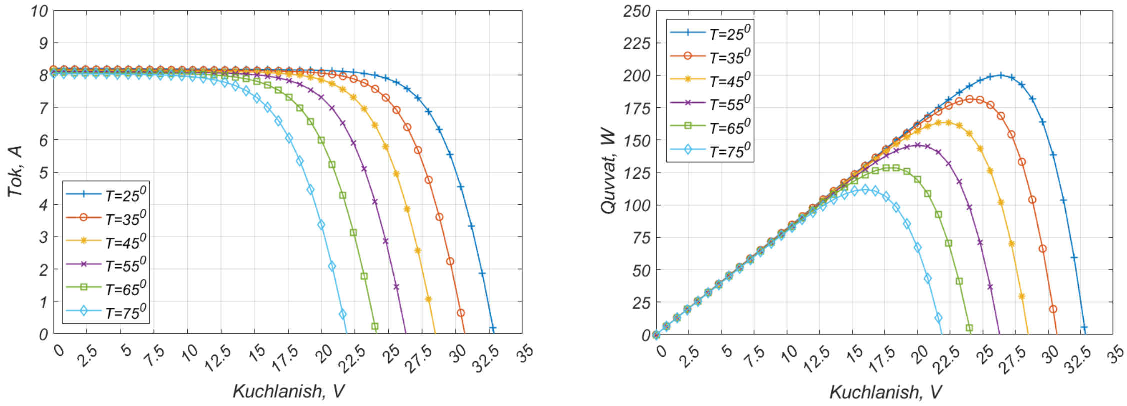
Furthermore, the module's back-surface temperature (Tm) as a function of ambient temperature, solar irradiance, and wind speed is modeled by [9]:

$$T_m = T_a + \frac{G}{800}(A - B \cdot v) \ (4)$$

Where: G – solar irradiance (W/m²); v – wind speed (m/s);

A and B – empirically determined coefficients representing, respectively, the upper temperature limit under low wind/high irradiance and the rate of temperature reduction with increasing wind speed.

Figure 1 shows the current–voltage (a) and power–voltage (b) characteristic curves of a solar module at a constant solar irradiance of 1,000 W/m² for varying ambient temperatures. The curves clearly demonstrate that both output voltage and power decrease with rising temperature. At 25 °C and 1,000 W/m², the maximum output power is 200 W; at 75 °C, it drops to approximately 110 W.

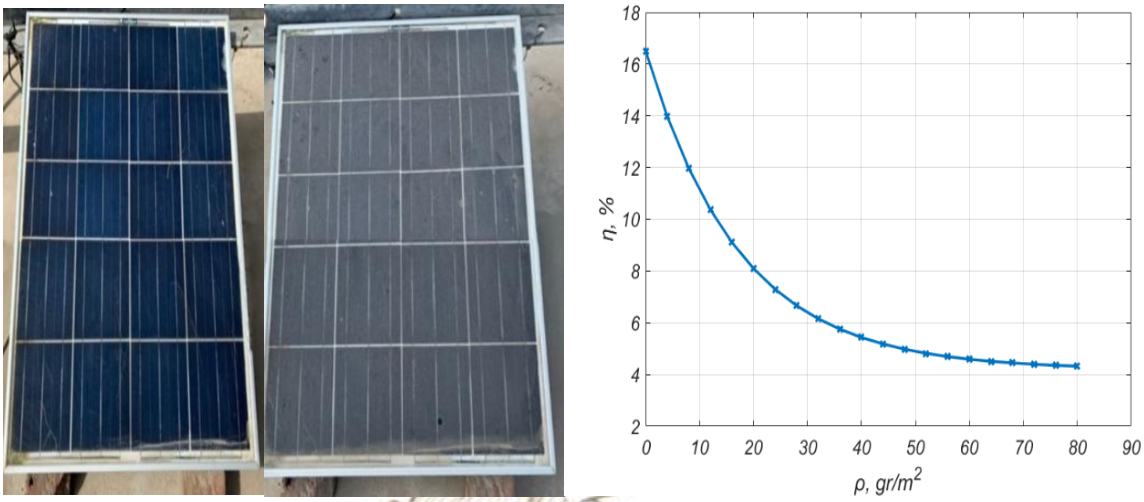


a) b)

Figure 1. Current–voltage (a) and power–voltage (b) characteristic curves of a solar module illustrating the effect of ambient temperature variation.

Figure 2 presents images of a clean PV panel (a), a dust-covered panel (b), and the relationship between dust accumulation and efficiency (c). Experimental results show that at a dust density of approximately 0.1 g/m², the efficiency reaches a maximum of

16%; at 80 g/m², it falls to 4%. These results were derived using the empirical equation (3).



a) b) c)

Figure 2. Clean solar PV panel (a), dust-covered state (b), and the relationship between dust accumulation and efficiency (c).

Figure 3 illustrates the dependence of PV panel temperature on wind speed at a solar irradiance of 1,000 W/m² and an ambient temperature of 40 °C. The results indicate that panel temperature decreases with increasing wind speed. Lower panel temperature correspondingly increases energy conversion efficiency.

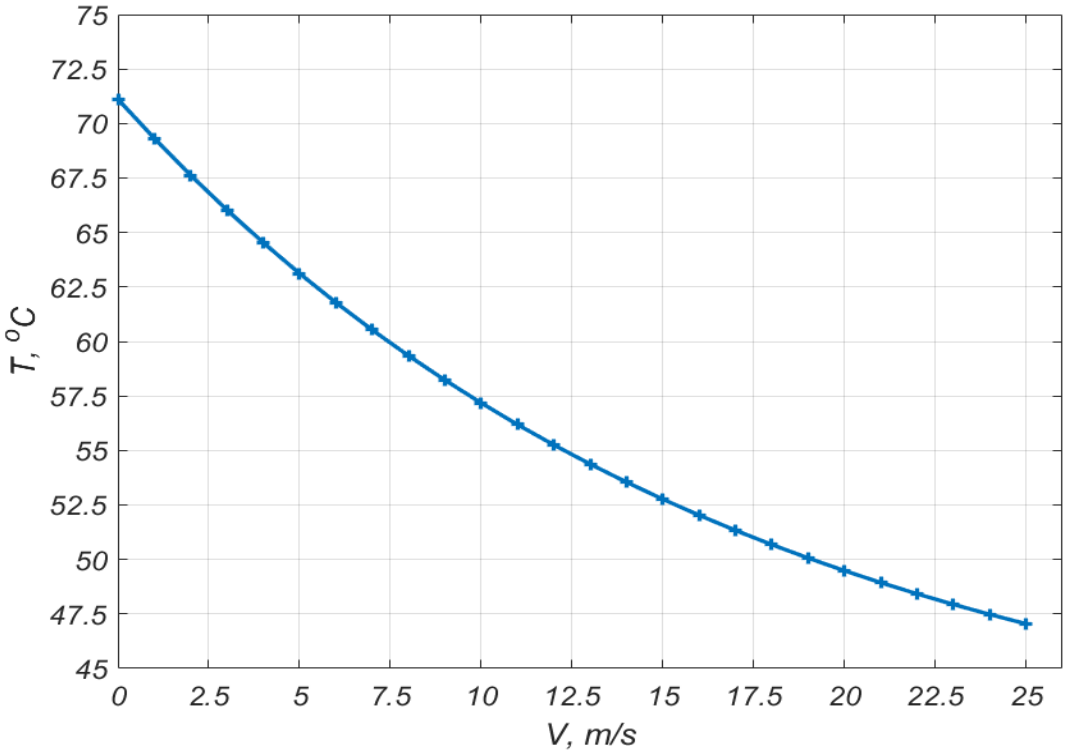


Figure 3. Relationship between solar PV panel temperature and wind speed.

Conclusion: The primary factors affecting solar PV panel efficiency are ambient temperature, solar irradiance, and wind speed. Maximum output (200 W) occurs at 25°C and 1000 W/m² irradiance, declining to ~110 W at 75°C. Dust accumulation of 80 g/m² can reduce efficiency from 16% to 4%. Wind speed plays a critical cooling role—reducing module temperature from 72°C (no wind) to 48°C at 25 m/s—thereby significantly improving performance.

REFERENCES

1. IRENA (2021). World Energy Transitions Outlook: 1.5°C Pathway. International Renewable Energy Agency, Abu Dhabi.

https://www.irena.org/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_World_Energy_Transitions_Outlook_Summary_2021_RU.pdf

2. Uzakov, G. N., Khozhakulov, S. M., & Uzakova, Y. G. (2017). Fundamentals of Alternative Energy Utilization. Tashkent: Fan va Texnologiya.

3. Alloev, K. R. (2021). Modern Energy and Its Development Prospects. Ed. A. U. Salimov. Tashkent: Fan va Texnologiyalar Nashriyot-Matbaa Uyi.

4. IEA (2023). Solar PV Deployment Trends. https://www.iea.org/energy-system/renewables/solar-pv

5. Decree of the President of the Republic of Uzbekistan No. PQ-57 (16.02.2023). https://lex.uz/uz/docs/-6385716

6. Uzokov, G. N., & Safarov, A. B. (2023). Mathematical Modeling of Solar Photoelectric Batteries in MATLAB/Simulink. IBAST, 3(9), 80–88. https://zenodo.org/records/8347989

7. Safarov, A. B., & Uzokov, G. N. (2023). Modeling of Hybrid Solar-Wind Energy Systems. Uzbekgidroenergetika, 2, 77–81.

8. Safarov, A. B., Uzokov, G. N., & Mamedov, R. A. (2023). Hybrid Solar-Wind Energy Installation. Intellectual Property Agency under the Ministry of Justice of Uzbekistan (FAP 02323, 17.08.2023).

9. King, D. L., et al. Photovoltaic Array Performance Model. Sandia National Laboratories, Albuquerque, NM. https://energy.sandia.gov/wp-content/gallery/uploads/SAND-2004_PV-Performance-Array-Model.pdf