

Impact of Thermal Parameters on the Performance of Photovoltaic Panels in Pump Water Solar Systems: A PVsyst Simulation Study

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Abstract: Solar energy has emerged as one of the most efficient and sustainable renewable sources for powering water pumping systems, particularly in rural and agricultural regions where conventional electricity grids are unavailable. Photovoltaic (PV) water pumping systems (WPS) provide an independent and cost-effective alternative that supports both energy and water security. In this study, a solar-powered water pumping system was designed and simulated using PVsyst software to drive an 11-horsepower submersible pump. The analysis investigated the influence of various PV panel technologies and thermal parameters, focusing mainly on the open-circuit voltage temperature coefficient (μVoc), on system efficiency and annual water yield. Simulation results demonstrated that PV panel technology and thermal behavior have a measurable impact on overall system performance, with lower (less negative) μVoc values leading to higher pumping efficiency and water output. The findings confirm that selecting panels with improved thermal characteristics significantly enhances system productivity and economic viability. This research contributes to optimizing PV-based pumping design for sustainable agricultural applications, promoting renewable energy adoption, and supporting the achievement of long-term water and energy sustainability goals.

1 INTRODUCTION

With the continuous global increase in energy demand and the progressive depletion of fossil fuel resources, renewable energy has emerged as a sustainable and reliable alternative for electricity generation. Among renewable sources, solar energy stands out for its abundance, environmental compatibility, and decentralized potential, particularly in regions lacking access to conventional electricity grids. One of its most practical agricultural applications is in powering water pumping systems, which play a crucial role in supporting rural development, food security, and sustainable agricultural growth [1].

As shown in Figure 1, global investment in renewable energy has grown substantially—from about 1.1 trillion US\$ in 2017 to nearly 1.75 trillion US\$ in 2023 reflecting the accelerating global transition toward sustainable energy production [2].

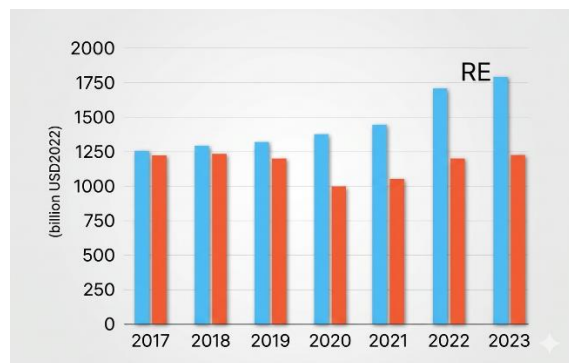


Figure 1: Global investment in renewable energy from 2017 to 2023.

Several studies have examined the performance and optimization of photovoltaic (PV) systems for agricultural applications across different geographical and climatic contexts. Jad Atallah et al. [3] investigated four installation scenarios for

agricultural PV systems in northern Lebanon: a fixed tilt system, a manually adjustable single-axis system, (repositioned once or twice daily), and an automated dual-axis tracking system. Their findings demonstrated that automated tracking enhanced solar-radiation capture by up to 38% compared to the fixed system, although the latter remained more cost-effective and easier to maintain.

Abdelhamid et al. [4] reported that these systems usually have a short payback period, often less than two years, which makes them financially appealing. Moreover, the availability of renewable energy resources supports the reclamation and cultivation of dry land. It also helps various livelihood activities and small businesses while contributing to sustainable development goals. Using solar-powered pumping systems is crucial for enhancing agricultural productivity and driving economic growth in underserved areas.

Mohammad Al-Smairan [5] designed a largescale PV-powered water-pumping system in the Mafraq region of Jordan, with a total capacity of 165 kWp, using three 55 kW inverters. The design balanced technical reliability and economic viability, ensuring stable water supply under local climatic conditions. Similarly, Partheeban [6] explored the impact of climate change on PV system efficiency and economic feasibility, emphasizing the link between energy infrastructure and agricultural.

Rittick Maity et al. [7] proposed the concept of agrivoltaics, integrating solar-energy production, water management, land use, and biodiversity into a unified system to optimize resource use and contribute to sustainable-development goals. In another related work, Rumbayan et al. [8] utilized PVsyst software to design and assess PV-based water-pumping systems, accounting for key design parameters such as orientation, tilt angle, electrical losses, and total-system efficiency.

Zakaria and Rabih, et al. [9], [10] designed and evaluated a hybrid renewable energy system (HRES) combining solar and wind resources to power a waterpumping system (WPS) in Al-Mudawara, a remote desert village in the Ma'an Governorate of Jordan. The system, intended to meet a daily energy demand of approximately 40.7kWh, was analyzed using HOMER simulation software to determine the most efficient configuration. Their study considered climatic and economic factors such as average monthly solar radiation (3.79kWh/m²), wind speed (6.31m/s), and financial constraints, ultimately confirming the technical and economic feasibility of the hybrid design under real-world desert conditions.

Despite these valuable contributions, limited attention has been devoted to the thermal behavior of PV modules, particularly the effect of the open-circuit voltage temperature coefficient (μVoc) on the performance of solar-powered water-pumping systems. Most previous studies focused primarily on system configuration, radiation modeling, and cost optimization, while the influence of panel thermal parameters on energy-conversion efficiency and water yield in PV water-pumping applications remains insufficiently explored [11].

To address this research gap, the present study employs PVsyst simulation software [12] to design and evaluate a solar-powered agricultural water-pumping system that drives an 11-horsepower submersible pump. The analysis focuses on how PV module technologies and their thermal coefficients (μVoc) affect system efficiency and the total annual volume of pumped water.

2 NECESSARY CONSIDERATIONS BEFORE SYSTEM DESIGN

Designing a solar-powered water pumping system requires careful evaluation of several technical, environmental, and operational factors to ensure optimal performance and long-term cost-effectiveness. The most critical considerations include:

- 1) Water source and site characteristics: accurate data about the water source such as depth, static and dynamic water levels, and elevation difference are essential to determine the total dynamic head (TDH) and to select a suitable pump;
- 2) Photovoltaic Panel Specifications. Selecting PV modules with appropriate electrical characteristics (nominal voltage, current, and efficiency) is vital. Special attention should be given to the temperature coefficient (μVoc), since panels with less negative μVoc values maintain better performance under high-temperature conditions;
- 3) Pump Type and Operation. The choice between submersible, centrifugal, or surface pumps depends on the depth of the source and the required discharge rate. Proper sizing ensures that the pump operates near its best efficiency point (BEP);

- 4) Photovoltaic System Configuration. The system can be direct-coupled, hybrid, or equipped with energy storage. The configuration should be selected based on application requirements reliability needs, and local climatic conditions [12].

3 DESIGN OF A PUMP WATER SOLAR SYSTEM

The design of a solar water pumping system involves a series of engineering calculations and decisions aimed at matching the hydraulic requirements with the available solar energy. The main steps are as follows:

- 1) Determining the Daily Water Demand The first step in system design is determining the amount of water required for the targeted activity;
- 2) Water Source Identification The selection of an appropriate pumping system depends on the nature of the water source;
- 3) Calculating the Required Flow Rate (liters/minute) according to the following equation:

$$Q = \frac{Q_{day}}{H_s} \quad (1)$$

Where:

- Q : flow rate (L/h) or (L/min);
- Q_{day} : Daily water intake required;
- H_s : Average hours of solar radiation (hours/day).

- 4) Calculating Total Dynamic Head (TDH) Total dynamic head (TDH) is defined as the sum of the heights a pump must overcome to pump water from the source to the discharge point. It includes: Static suction head, and Static delivery head: They are calculated based on the length, diameter, and number of connections of the pipes Figure 2. Total head is calculated using the equation:

$$TDH = H_{suction} + H_{delivery} + H_{friction} \quad (2)$$

- 5) Pump Power Calculation After determining the flow rate and TDH, the electric pump power can be calculated using the following equation:

$$P_{pump} = 0.0001635 \times \frac{Q \times TDH}{\eta_p \cdot \eta_{inv}} \quad (3)$$

Where:

- Q : Flow rate (L/min);

- P_{pump} : Pump power required (kW);
- η_p : Pump efficiency (usually taken as 60%);
- η_{inv} : Inverter efficiency (typically 90%);
- TDH : Total dynamic height (meters).

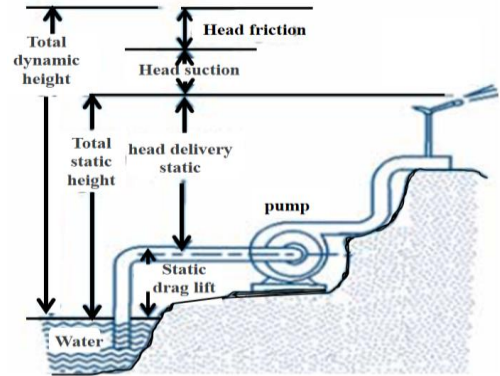


Figure 2: Dynamic pumping heights.

- 6) Sizing the PV Array (P_{PV}). The solar array power required to operate the system is calculated. The array power is calculated using the following equation:

$$P_{PV} = 1.5 \times P_{pump} \quad (4)$$

The appropriate number of solar panels is selected based on the capacity of each panel $P_{modules}$ according to the relationship:

$$N_{module} = \frac{P_{PV}}{P_{module}} \quad (5)$$

Designing a solar-powered water pumping system requires a comprehensive analysis that encompasses the hydraulic and technical aspects of solar energy. The required flow volume and heights are determined, and the appropriate pump and solar array are then selected based on approved engineering standards. Relying on solar energy in this context contributes to reducing carbon emissions, decreasing operating costs, and achieving sustainable water supply, especially in rural and remote areas [12].

4 CASE STUDY

The farm under study is located in a geographical area within the coordinates 34.95N, 38.48E (Fig. 3), at an elevation of approximately 896m above sea level.

This farm relies primarily on pumping water from a groundwater well to meet its daily needs, with an estimated annual water consumption of 36,500

m³/year, or an average of 100m³/day. The well-used for pumping is approximately 100m deep and 30cm in diameter. The water is stored in a 150m³ tank to ensure a continuous water supply and to overcome periods of dryness. PVsyst software was used to analyze and prepare the technical design for the photovoltaic pumping system, taking into account the climatic conditions and geographical location. The solar panels were installed on a fixed platform tilted 33.2 degrees south (the optimal angle for the region), ensuring maximum solar energy yield throughout the year. Design results via PVsyst: Solar panel system capacity: 18.4(kWp) Submersible pump capacity: 14.7(kW) Inverter capacity: 15 kilowatts (kW) Inverter type: MPPT (Maximum Power Point Tracking) and VDF (Variable Frequency Drive) control Estimated hydraulic losses: approximately 2%, including losses due to pipe length. The main pipeline is 140m long, DN125 (5-inch), and has three elbows to increase flow resistance. Table 1 shows the specifications of the inverter used, which is based on Maximum Power Point Tracking (MPPT) technology and uses a Variable Frequency Drive (VFD) control method.

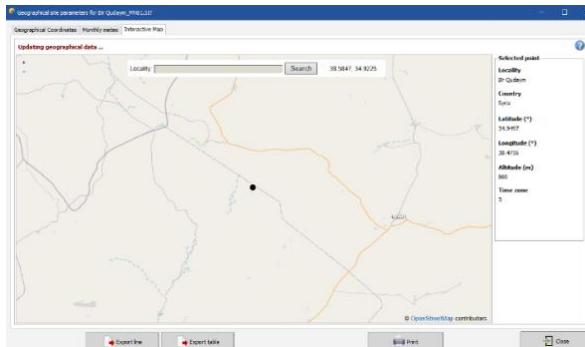


Figure 3: The studied site.

Table 1: Specifications of the Inverter Used.

Model	P_{Output} (kW)	V_{out} (V)	V_{min} (V)	V_{mpp} (V)	I_{max} input (A)
PB15KH 380Vac	15	850	500	850	24

Table 2 demonstrates the specifications of the submersible pump used, which is equipped with an

Table 2: Specifications of the submersible pump used.

Model	P_{max} (kW)	I_{max} (A)	V (V)	Pump layout	Motor type	Efficiency %
PSk2-15 C-SJ17-18	15	15.7	700	Deep well	Three-phase induction motor	41.9-55.5

induction three-phase alternating current motor with a voltage (380VAC).

Since most photovoltaic modules operate in outdoor environments, where the panels are exposed to variable climatic conditions such as temperature and relative humidity, unknown parameters are affected by factors such as solar radiation and temperature. Therefore, it is necessary to adjust these parameters to match actual environmental conditions [13], [14]. To study the effect of the PV panel parameters used on the daily amount of water pumped, two different scenarios will be analyzed.

4.1 Scenario 1: Using the Same Model and Nominal Power, with Different Manufacturing Technologies

In this scenario, all parameters related to the photovoltaic system were fixed, except for the solar panel manufacturing technology. The goal is studying the effect of the manufacturing technology on the daily pumped water volume, as well as the temperature coefficient (μV_{oc}), which affects performance under actual operating conditions. Solar panels with a uniform nominal power of 535W from the same manufacturer were used to ensure consistency in quality and manufacturing standards, with only the technology type being changed (e.g., Monocrystalline PERC, Polycrystalline, or Bifacial). The technical specifications for each panel type are shown in Table 3, including efficiency, nominal voltage (V_{mp}), nominal current (I_{mp}), temperature coefficient (μV_{oc}), and other relevant characteristics.

Based on the simulation results, the values and data shown in Table 4 were obtained, demonstrating the impact of different panel technologies on the overall performance of the system and the amount of water pumped daily: Table 4 of results extracted from the simulation is included here, including comparative parameters such as the amount of water pumped (m³/day), efficiency, temperature coefficient, and others as needed. Figure 4 shows that the annual pumped water volume increased by 49m³ when using the best solar panel technology (LR5-72HIBD-535M G2 Bifacial), thanks to its relatively low temperature coefficient (-139mV/°C), despite both technologies having the same nominal power (535W).

Table 3: Technical specifications for each panel technology used.

	LR5-72HIBD-535M G2 Bifacial	LR5-72HBD-535M G2 Bifacial	LR5-72HIH-535M G2
Power (W_p)	535	535	535
$V_{oc}(V)$	49.35	49.35	49.35
$I_{sc}(A)$	13.78	13.78	13.78
Coefficient of temperature ($mV/^{\circ}C$)	-139	-142	-141
$R_s(\Omega)$	0.30	0.20	0.21
$R_{shunt}(\Omega)$	1000	1100	2000
N° Cells	72×2	72×2	72×2
Cell efficiency %	22.49	22.47	20.76
Module efficiency %	20.76	20.74	20.76

Table 4: Simulation results.

	HIBD 535 MG2	72HBD-535M G2 Bifacial	LR5-72HIH-535M G2
Water pumped ($m^3/year$)	35686	35637	35653
System efficiency (%)	69.1	69.8	69.6
Pump efficiency (%)	49.5	49.6	49.6
Performance ratio Pr	0.61	0.607	0.608
Specific energy (kWh/m^3)	0.6	0.6	0.6

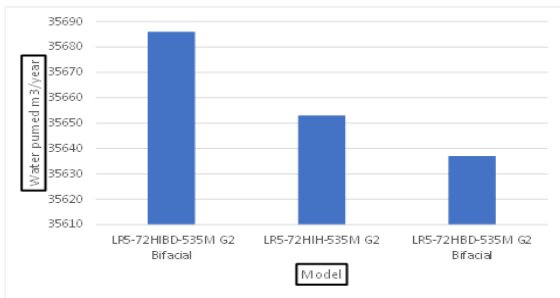


Figure 4: The annual pumped water.

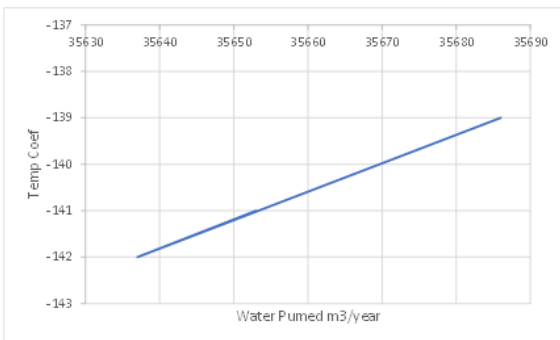


Figure 5: Relationship between annual pumped water and Temperature coefficient.

This improvement in performance clearly contributes to enhancing the efficiency of water supply and enhances the long-term economic feasibility of the project through the savings achieved

over the system's lifetime. Figure 5 demonstrates the relationship between the panel's thermal coefficient and the amount of water pumped is inverse, with the amount of water pumped increasing as the thermal coefficient (μV_{oc}) decreases.

Therefore, most manufacturers seek to improve the performance of solar panels by enhancing their thermal properties, which contributes to increased efficiency, economic savings, and improved quality.

4.2 Scenario 2: Using Different Models of Photovoltaic Panels with the Same Power

On the other hand, photovoltaic modules from different manufacturers, all with the same rated power of 555 W, were selected from the PVsyst software library. In response to the reviewer's comment, a broader set of commercially available modules was included to cover a wider range of thermal coefficients and manufacturing technologies while maintaining the same nominal power. The selected modules span a μV_{oc} range of approximately -105 to -148 $mV/^{\circ}C$ and represent different cell technologies, including PERC, TOPCon, bifacial, and half-cut designs. The simulations were carried out under identical design conditions and without changing the other system parameters in order to isolate the effect of the thermal coefficient (μV_{oc}) on the annual pumped water volume and the overall system efficiency. Figure 6 shows the annual pumped

water obtained for the investigated PV module models.

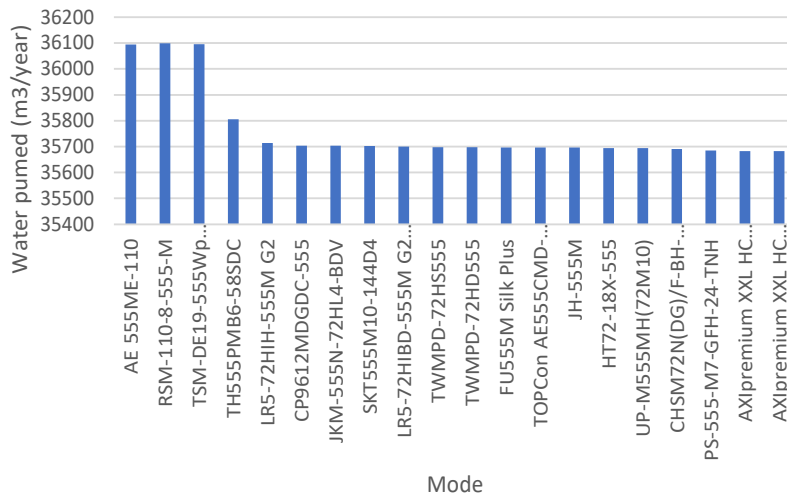


Figure 6: Amount of water pumped annually.

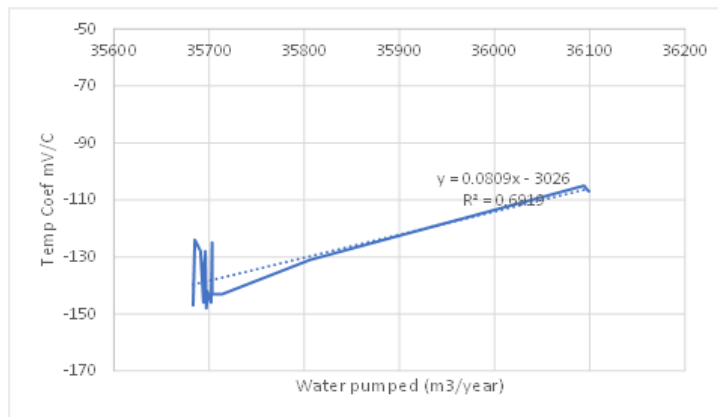


Figure 7: Relationship between μV_{oc} and the amount of water pumped annually.

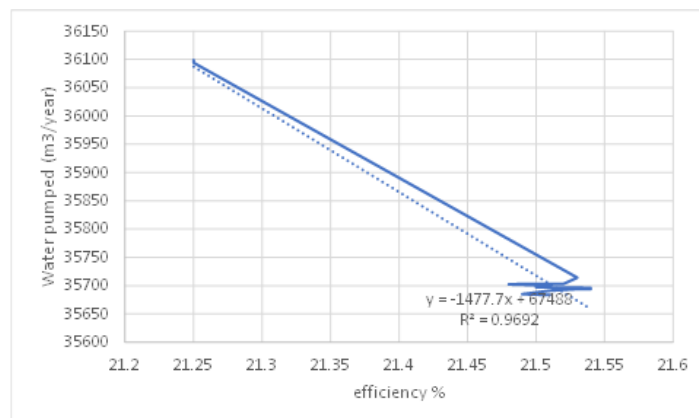


Figure 8: Relationship between efficiency and the amount of water pumped annually.

Figure 6 shows the annual pumped volume of water using different solar panel models with the same rated capacity. There is a slight variation in performance between models, with some panels showing higher water pumping efficiency. This reflects the influence of the thermal coefficient and other technical characteristics of each model, such as efficiency, temperature coefficient, and the type of cells used (PERC, Half-cut, TopCon, etc.). This analysis demonstrates the importance of selecting the appropriate model to achieve the highest possible productivity in water applications. It is noticeable from Figure 6 that the amount of water pumped increases as the thermal coefficient of the solar panels decreases. The difference in the amount of water pumped annually amounts to approximately 411m³/year, which represents a significant water saving, in addition to achieving significant economic savings over the project's estimated lifespan of 25 years. Figure 7 shows the relationship between the thermal coefficient of solar panels and the amount of water pumped annually, where an inverse relationship is observed between the two variables.

Figure 7 shows the relationship between the annual pumped water quantity (m³/year) and the thermal coefficient of the solar panels (Temp. Coef mV/°C). The general trend of the data reveals an inverse relationship, with the pumped water quantity increasing as the thermal coefficient value decreases. The linear regression equation ($y=0.0809x-3026$) supports this trend, with a coefficient of determination $R^2=0.6041$, indicating a moderately strong correlation between the two variables. This confirms that the panels' good thermal performance positively impacts the pumping efficiency and, consequently, the PV system's productivity.

The relationship between the model's output (efficiency) and the amount of water pumped annually is demonstrated in the Figure 8. The data show a clear linear convergence, indicating that increasing the efficiency of the solar panel leads to improved pumping system performance and increased annual water production.

The relationship between solar panel efficiency and the amount of water pumped is analyzed as the following: The data shows a weak direct relationship between solar panel efficiency (yield) and the amount of water pumped annually, as increases in efficiency are typically associated with a slight increase in the amount of water pumped. However, this relationship is not strong, and the following points can be observed from the simulation results:

- 1) Some models with lower efficiency (e.g. 21.25%) achieved higher water pumping volumes of about 36094–36099 m³/year;
- 2) While higher efficiency models (21.48–21.54%) achieved relatively lower pumping volumes, in the range of 35683–35714 m³/year;
- 3) This trend is contrary to what is theoretically expected, as increased efficiency is supposed to lead to increased energy production and thus water pumping;
- 4) This discrepancy is likely due to other reasons, such as: Different thermal coefficients of the panels. Different manufacturing techniques (such as PERC, TopCon, half-cut). Other electrical properties were not directly considered;
- 5) The efficiency range in the models studied is relatively narrow (with a difference of no more than 0.29%), making the effect of efficiency alone insufficient to explain the differences in pumping quantities.

The analysis appears a weak direct relationship between solar panel efficiency (yield) and thermal coefficient (μ Voc). Higher-efficiency panels tend to have a less negative (μ Voc), indicating better thermal performance. This relationship can be illustrated in Table 5, which displays data on the various solar panel models used in the simulation, in terms of efficiency and (μ Voc).

Table 5: Analysis results.

Variable	Range	Average	Standard deviation
Efficiency %	21.25-21.54	~21.43	0.09
μ Voc (mV/°C)	(-148)(-105)	~-132.6	14.2

By analyzing the data in Table 5, the following points can be noted:

- 1) With increasing efficiency (from 21.25 to 21.54), we observe: A slight improvement in the thermal coefficient (from -107 to -128 on average), and a large scatter in the data;
- 2) Best Performance: TOPCon AE555CMD-144BDS (21.54%, TFC -128), HT72-18X-555 (21.54%, TFC -135);
- 3) Worst performance: Models with an efficiency of 21.25% (Temperature coefficient of -105 to -107);
- 4) Impact of different technologies: TOPCon technology (in the best model) exhibits better thermal performance, Conventional

technologies exhibit a more negative thermal coefficient;

- 5) The expected inverse relationship: The less negative the thermal coefficient (closer to zero), the lower the efficiency loss with increasing temperature. This is consistent with results showing higher efficiency when the thermal coefficient is improved.

The μVoc coefficient is used during system sizing to estimate the maximum voltage a photovoltaic array can reach under the worst-case conditions, such as low temperatures. This evaluation acts as a crucial safety check when designing a photovoltaic array. It helps ensure that the maximum allowable voltage of the electrical components is not exceeded. It's important to note that values calculated using PVsyst software, based on its internal model, may sometimes result in a higher $\text{Voc}(T_{\text{min}})$ voltage compared to values generated by other design programs that rely directly on the manufacturer's μVoc coefficient.

5 CONCLUSIONS

The temperature of photovoltaic panels plays a critical role in determining the electrical and thermal performance of solar water pumping systems. In this study, the influence of the open-circuit voltage temperature coefficient (μVoc) on overall system performance was analyzed using PVsyst simulation software. Two main scenarios were examined: Scenario 1: Panels of identical power (535W) but different technologies-Monofacial, Bifacial, and HIT. Results showed that bifacial modules with a less-negative thermal coefficient increased the annual water yield by approximately 49 m³ compared to other types.

Scenario 2: Different commercial panels of equal rated power (555W) from multiple manufacturers. Although the nominal efficiencies were nearly identical, differences in μVoc produced variations of up to 411 m³ per year in the pumped-water volume. A clear inverse relationship between μVoc and system efficiency was observed: panels with improved thermal behavior (less-negative μVoc) achieved higher energy conversion and water output. Overall, the findings confirm that focusing solely on nominal efficiency is insufficient when selecting PV modules for pumping applications. Instead, thermal performance and manufacturing technology (TopCon, Bifacial, HIT) should be considered as decisive design factors, particularly in hot and arid climates.

It is recommended to conduct a detailed technoeconomic feasibility assessment using professional simulation tools such as PVsyst prior to project implementation, to ensure maximum return over the system's lifetime (25 years or more).

Future research should also explore adaptive control strategies and hybrid energy models to further enhance the sustainability and reliability of solar powered water-pumping systems.

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