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SOLAR PUMPS FOR SUSTAINABLE AGRICULTURE: A STUDY ON ECONOMIC VIABILITY AND TECHNICAL PERFORMANCE

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ABSTRACT

Water scarcity and power availability are critical issues in agriculture, especially in developing countries. The need to reduce water and electricity consumption while increasing production necessitates innovative solutions. Solar photovoltaic (PV) water pumping systems present a viable option, offering cost-competitiveness, environmental benefits, and energy security. This study examines the techno-economic performance of a solar PV water pump installed at RTTC, Junagadh Agricultural University, from November 2019 to September 2022. The solar PV system, with a 5 HP, 3-phase AC motor, and 20 solar panels, was designed to operate without a battery, using a manual tracking system to optimize performance. The system's performance depended on solar radiation, total dynamic head, water requirements and sunshine hours. Data collected revealed that solar radiation, ranging from 257.53 to 1050.09 W/m², significantly affected power generation and system efficiency. The average solar panel output ranged from 811.58 to 4532.79 W/32.8m², with the highest output during the *Rabi* season. Water horsepower (WHP) varied from 0.73 to 1.72 HP, depending on the season and time of day. Pump discharge rates varied between 2.02 to 4.18 liters per second (lps). The system's average array efficiency ranged from 8.26% to 11.64%, while pump efficiency ranged from 25.30% to 68.58%, with higher efficiencies observed in the morning due to lower head requirements. Overall system efficiency varied from 3.19% to 6.77%, with higher efficiencies during periods of increased solar radiation. Economically, the solar PV pump's operating cost was significantly lower (` 73.19/hour) compared to electric (` 80.18/hour) and diesel pumps (` 230.36/hour). Additionally, solar pumps are environmentally friendly, reducing carbon emissions associated with electricity and diesel use. Farmers in the South Saurashtra Agroclimatic Zone are recommended to adopt solar PV pumps for higher efficiency, lower operating costs, and environmental benefits. Optimal operation times are between 10 am and 4 pm, ensuring effective irrigation and maximizing system performance. This sustainable approach can significantly enhance agricultural productivity and support socio-economic development in semi-arid regions.

Key words : Solar photovoltaic water pump, Techno-economic performance, Agricultural sustainability, Water and energy efficiency.

Introduction

Water scarcity and available energy resources have emerged as critical challenges in the agricultural sector, particularly in developing countries where agricultural productivity is essential for food security and economic stability. The increasing demand for food, driven by population growth and changing diets, intensifies pressure on already limited freshwater resources. In this context, innovative solutions that enhance water management while ensuring sustainable energy use are imperative. Solar photovoltaic (PV) water pumping systems offer a promising alternative, integrating renewable energy to address the dual concerns of water scarcity and fossil fuel dependency. These systems provide not only cost-effectiveness, but also significant environmental advantages by reducing carbon emissions linked to traditional pumping methods. Given the complex interplay of factors such as solar radiation, hydraulic head and operating hours, understanding the techno-economic performance of solar PV pumps is essential to optimize their implementation in agriculture. The ongoing research on solar PV water pumping systems highlights the need for technical feasibility studies coupled with economic assessments to facilitate broader adoption among farmers. By ensuring efficient water pumping during peak sunlight hours and aligning agricultural practices with sustainable energy use, farmers can enhance their yield while minimizing operational costs. In this overview, we will examine the existing literature surrounding the techno-economic performance of solar PV pumps in agriculture, analyze their practical applications in various contexts, and discuss their role in advancing agricultural sustainability and energy efficiency.

The application of solar PV water pumping systems in agriculture has garnered significant attention in recent years, driven by the urgent need for solutions to combat water scarcity and enhance energy security. The efficiency of these systems not only stems from their reliance on renewable energy but also from advancements in technology that have made them increasingly cost-competitive compared to traditional diesel and electric-powered pumps. Multiple studies have demonstrated that solar PV water pumps can effectively meet varying irrigation needs across diverse climatic conditions, resulting in improved agricultural outputs (Elnozahy *et al.*, 2024 and Verma *et al.*, 2021). Research indicates a pronounced difference in operational costs between solar PV pumps and conventional pumping systems. For instance, findings suggest that solar pumps can reduce operational expenses significantly, with reports indicating costs as low as ` 73.19 per hour compared to ` 230.36 per hour for diesel pumps (Elnozahy *et al.*, 2024). Furthermore, the environmental implications of shifting to solar-powered systems are substantial, as they contribute to reducing greenhouse gas emissions associated with fossil fuel use (Hilarydoss, 2023).

Odeh *et al.* (2006) conducted a study on the economic viability of photovoltaic (PV) water pumping systems compared to diesel engine pumping systems, finding that PV systems are a viable option for off-grid water pumping. Mokeddem *et al.* (2011) analyzed the performance of a direct-coupled PV water pumping system consisting of a 1.5 kW PV array, a DC motor, and a centrifugal pump. The study revealed that the motor-pump system's efficiency did not exceed 30%, indicating that direct-coupled systems are suitable for low-head irrigation in remote areas. Shiv Lal *et al.* (2013) examined the performance of a PV array-based water pumping system located in Kota, Rajasthan (25.18° N, 75.83° E). The system used a 2 hp DC motor and a 2200W PV array (comprising 10 panels of 225W each) to pump water at a 30 m head. The maximum discharge was recorded at 163 liters per minute between 11 AM and 2 PM, with a PV power output of 75 to 85 W/m², and the system operated for approximately 8 hours in November during the winter season. The total daily discharge was 70,995 liters, which exceeded the average discharge provided by the manufacturer for a 50 m depth. The study concluded that PV array-based water pumping systems are a suitable and feasible option for off-grid and drip irrigation systems, particularly in interior areas of Kota where there are more than 250 clear sky days annually.

Moreover, studies emphasize that the performance of solar PV pumping systems is influenced by factors like solar radiation and water requirements, which directly affect their operational efficiency. Experimental setups have shown considerable variations in pump discharge rates and efficiencies throughout different seasons and times of day, highlighting the importance of optimized system design and operation hours (Habib *et al.*, 2023). The broader socio-economic benefits of adopting solar PV systems in agriculture are also acknowledged, particularly in semi-arid regions. Implementing such technology not only improves water and energy efficiency but also promotes agricultural resilience against climate variability, which is crucial for farmers facing the adverse effects of climate change. The primary objectives of this study are twofold: First, to assess the water pumping potential of the solar photovoltaic (PV) pump system; and second, to evaluate the economic viability and cost-effectiveness of using solar PV pumps in agricultural applications.

Materials and Methods

The experiment was conducted at the Research cum Demonstration Farm of Centre of Excellence on Soil and Water Management, Research Testing and Training Centre, Junagadh Agricultural University, Junagadh. It is located at 21.5°N latitude and 70.44°E longitude with an altitude of 82.92 meter above mean sea level. The experimental details included conducting statistical analysis using an appropriate tool across three seasons: winter, summer and monsoon. The solar water pump operated one day per week for a total of 17 weeks per season, with hourly operation from 8:00 AM to 6:00 PM. The solar water pump system specifications included a 5 hp AC pump, 20 solar panels each with an output of 240

W, resulting in a total output of 4800 W. The well depth was 30 ft and the tracking system was manual.

The existing solar pumping system consisted of an AC pump, an inverter, and a PV array. This system was designed to directly drive the pump motor without the use of a battery. The PV array, composed of multiple solar panels connected in series, acted as the power source by converting absorbed solar radiation into electrical energy. The solar pumping inverter controlled the entire system operation, converting the DC power produced by the PV array into AC power to drive the pump. The pump, powered by a 3-phase AC motor, drew water from the well.

The solar water pump was operated once a week from November 2019 to September 2022. During the experiment, nominal PV power and daily irradiation at the site of operation were monitored. Hourly measurements included the output of the solar panels from the inverter using a watt meter, the pump discharge using a water meter at the outlet, and the pumping head. Observations recorded included the output from the panel array, pumping discharge in cubic meters per hour (m^3/hr) and the pumping head in meters (m). Diurnal variations in current, voltage, and solar output in relation to solar radiation were manually recorded at one-hour intervals from 9:00 AM to 5:00 PM using the inverter of the solar photovoltaic system. Solar radiation (W/m^2) was also manually recorded at one-hour intervals using a pyranometer on the solar photovoltaic system. The specifications of the solar photovoltaic pump include a 5 hp, 3-phase AC pump. The system is equipped with 20 solar panels, each with a maximum power output (Pmax) of 240 W. The maximum power voltage (Vmp) is 29.0 V, and the maximum power current (Imp) is 8.28 A. The short circuit current (Isc) is 8.89 A, and the open circuit voltage is 36.0 V. The total output of the system is 4800 W. The module size is 1600 mm by 900 mm, and the tracking system is manual.

Solar Radiation

Solar radiation was calculated by measuring the intensity of sunlight reaching the Earth's surface in watts per square meter (W/m^2). Measurements were taken during different seasons, and data was collected between 11:00 am to 2:00 pm and during morning and evening hours. The average solar radiation values were then recorded and analyzed across rabi, summer, and *kharif* seasons. The calculations considered variations in weather conditions and the nonlinear nature of solar radiation.

Solar Panel Output

The solar panel output was calculated by measuring the power generated per 32.8 square meters of the panel surface across different seasons. The output was recorded at regular intervals and averaged for rabi, summer, and kharif seasons, as well as for the entire year. The maximum output was observed during the rabi season from 2019 to 2022. The formula used for calculating the solar panel output was:

Solar Panel Output (W) = Power Generated (W)/ Surface Area (32.8 m^2) (1)

PV array efficiency

The performance of solar water pumping system was depending on the availability of solar radiation at location, total dynamic head, total quantity of water requirement, sunshine hour, hydraulic energy etc. Overall SPV pumping system efficiency was calculated using following equation.

$$\text{PV array efficiency} = \frac{\text{Output}}{\text{Input}} \times 100 \quad (2)$$

$$= \frac{\text{Power delivered by array}}{\text{Corresponding solar radiation}} \times 100$$

Pump Efficiency

Pump efficiency is calculated as the ratio of the power required to lift water to the power delivered by the array, expressed as a percentage. This efficiency metric indicates how effectively the system converts the available power into useful work for water lifting.

$$\text{Pump efficiency (\%)} = \frac{\text{Power required to lift water}}{\text{Power delivered by array}} \times 100 \quad (3)$$

Overall SPV pumping system efficiency (%)

$$= \frac{\text{Pump efficiency}(\%)}{100} \times \frac{\text{PV array efficiency}}{100} \times 100 \quad (4)$$

Water horse power is the minimum power required to move water. Diurnal variation of water horse power with respect to solar radiation in a day was calculated at one-hour interval from 09:00 am to 05:00 pm based on discharge of solar pump and it was calculated as per following equation.

$$\text{WHP} = \frac{Q \times H}{75} \quad (5)$$

Economics

The economic analysis compared the operating costs per hour of solar photovoltaic (PV), electric and diesel pumps, considering various parameters and assumptions.

The calculation revealed the following costs: ` 73.19 per hour for the solar PV pump, ` 80.18 per hour for the electric pump and ` 230.36 per hour for the diesel pump.

Results and Discussion

Solar radiation (W/m^2)

The solar radiation, which is a nonlinear source effects the power generation from the PV array. The PV array operating point changes with the change in weather conditions. Average solar radiation ranges from 505.36 to 1050.09 W/m^2, 460.87 to 979.98 W/m^2, 257.53 to 812.42 W/m^2 and 407.92 to 943.91 W/m^2 during rabi, summer, kharif season and yearly respectively. Highest solar radiation measured during Rabi season November 2019 to February 2022 between 11:00 am to 2:00 pm and lowest was observed during July 2019 to Sept 2022. Visible spectrum of light reaching to the earth surface has longer wavelengths during morning and evening hours bearing less intensity values of solar radiation compared to greater intensity radiations at afternoon hours.

Solar Panel Output

Average solar panel output ranges from 1710.52 to 4532.79 W/32.8m^2, 1502.07 to 4191.91 W/32.8m^2, 811.58 to 3331.35 W/32.8m^2 and 1341.39 to 4018.68 W/32.8m^2 during rabi, summer, kharif season and yearly respectively. Maximum solar panel output of 4532.79 W/32.8m^2 was also observed in rabi season 2019 - 2022.

Water horse power (hp)

The power obtained from the PV array is sufficient enough to impart the maximum power to the pump working. It increases gradually with increase in solar radiation up to noon hour's and remains constant during the afternoon and falls during the latter part of day after 15:30 h. Average water horse power ranges from 1.03 to 1.72 hp, 1.10 to 1.63 hp, 0.73 to 1.31 hp and 0.95 to 1.54 hp during rabi, summer *kharif* season and yearly respectively. Maximum water horse power of 1.72 hp was observed at 12:00 pm during rabi season.

Pump discharge (lps)

Depending on the solar irradiance and total head, the average flow rates during a day varies between 2.75 to 4.18 lps, 2.95 to 4.02 lps, 2.02 to 3.29 lps and 2.57 to 3.80 lps during rabi, summer *kharif* season and yearly respectively.

Array efficiency (%)

Average array efficiency during a day range from 8.97 to 11.64%, 8.57 to 11.28%, 8.26 to 10.71% and 8.62 to 11.21% during *rabi*, summer, *kharif* season and yearly respectively. It was observed that panel efficiency increased from morning time approximately 10:00 am to 11:00 am, then after it decreases and remain at par up to 04:00 pm. Reduction of panel efficiency during noon time may be due to higher panel temperature (Similar results were reported by Lal *et al.* (2013).

Pump efficiency (%)

Solar photovoltaic water pump is function of solar irradiation and total head. Linear relationship was observed between pump efficiency and solar radiation. As solar radiation increased the pump efficiency was increased. Pump efficiency during a day varies from 25.78 to 42.11%, 25.30 to 56.41%, 25.64 to 68.58% and 25.58 to 55.34% during *rabi*, summer, *kharif* season and yearly respectively. It is higher during morning time which may be due to lower head.

Overall system efficiency (%)

Average total system efficiency during a day varies from 3.45 to 4.46%, 3.19 to 6.00%, 3.28 to 6.77% and 3.39 to 5.71% during *rabi*, summer, *kharif* season and yearly respectively. The average maximum system efficiency 6.77% was observed at 05:00 pm (257.53 W/m^2). Similar results were reported by Narale *et al.* (2013) and Khedkar (2017). The efficiency increases sharply during morning and remain almost constant (with variations < 5%) for the mid noon to late afternoon. At lower solar intensity, when the input power available to the solar photovoltaic water pump system is lesser, the total system efficiency is also very less. For the low solar intensity, the higher pumping head gives the lowest system efficiency. With the increase in solar radiation, the input power to the solar photovoltaic water pump system starts increasing which causes the components to operate near or at its rated conditions, giving higher efficiencies.

Economics

The operating cost per hour of the solar photovoltaic pump, electric pump and diesel pump was calculated considering various parameters and assumptions and presented in Table 2.

It was observed that operating cost per hour of solar photovoltaic pump was lower (` 73.19/hour) in comparison with electric pump (` 80.18/hour) and Diesel pump (` 230.36/hour). Use of solar photovoltaic pump is environmentally friendly and do not cause any atmospheric pollution. Moreover, average emission of carbon dioxide for generation of electricity from thermal power plant is about 1.58 kg of CO_2/kWh, and thus, for using a 1.0 hp electric pump, for 1000 h/year will produce about 1520 kWh × 1.58 kg/kWh = 2402 kg of CO_2. On the other hand, if one use diesel pump, it will consume about 112 L

Table 1 : Diurnal variation of solar pump parameters.

Time	Solar Intensity (W/m^2)	Current (Ampere per 32.8 m^2)	Voltage (per 32.8 m^2)	Solar panel output (W per 32.8 m^2)	Water horse power (hp)	Discharge (lps)	Array Effi. (%)	Pump Effi(%)	Overall system effi.(%)
***Rabi* Season**									
9:00 AM	549.47	3.62	445.55	1840.91	1.11	2.95	8.97	42.11	4.46
10:00 AM	818.16	5.25	525.87	3151.27	1.41	3.57	10.26	30.97	3.72
11:00 AM	952.97	6.47	541.89	4002.92	1.62	4.00	11.21	27.58	3.64
12:00 PM	1039.35	6.99	568.95	4532.79	1.72	4.18	11.64	25.78	3.54
1:00 PM	1050.09	6.99	562.25	4480.62	1.72	4.17	11.39	26.11	3.50
2:00 PM	1003.95	6.67	540.78	4118.74	1.62	3.99	10.95	26.86	3.45
3:00 PM	909.66	5.82	531.85	3536.76	1.50	3.76	10.36	28.99	3.54
4:00 PM	775.37	4.95	504.13	2843.34	1.32	3.39	9.77	31.58	3.64
5:00 PM	505.36	3.24	462.45	1710.52	1.03	2.75	9.04	41.03	4.36
Summer Season									
9:00 AM	574.82	3.44	456.85	1892.64	1.23	3.24	8.59	48.97	5.13
10:00 AM	794.89	4.99	499.71	2954.90	1.41	3.62	9.64	33.13	3.87
11:00 AM	924.92	6.13	528.38	3797.32	1.55	3.87	10.68	28.45	3.58
12:00 PM	979.98	6.68	543.18	4191.91	1.55	3.88	11.28	25.30	3.36
1:00 PM	957.17	6.45	535.45	3972.37	1.63	4.02	11.00	27.31	3.59
2:00 PM	926.37	6.23	513.69	3668.23	1.42	3.60	10.53	25.48	3.19
3:00 PM	860.82	5.67	500.43	3262.20	1.31	3.41	10.06	27.07	3.26
4:00 PM	664.48	4.26	466.59	2296.00	1.24	3.25	9.23	36.93	4.10
5:00 PM	460.87	2.93	423.34	1502.07	1.10	2.95	8.57	56.41	6.00
***Kharif* Season**									
9:00 AM	295.18	2.00	385.32	954.84	0.74	2.02	8.51	57.17	5.67
10:00 AM	548.69	3.49	445.76	1981.16	1.07	2.77	9.45	38.31	4.28
11:00 AM	704.85	4.69	468.94	2789.48	1.31	3.29	10.34	33.28	4.07
12:00 PM	812.42	5.41	492.83	3331.35	1.24	3.16	10.71	25.64	3.28
1:00 PM	763.89	5.08	483.97	3095.97	1.26	3.21	10.57	27.98	3.55
2:00 PM	676.58	4.46	467.36	2635.78	1.29	3.19	10.13	34.07	4.09
3:00 PM	541.77	3.56	444.08	1998.75	1.06	2.79	9.61	38.74	4.44
4:00 PM	393.52	2.59	414.67	1366.50	0.84	2.28	9.11	45.24	4.87
5:00 PM	257.53	1.70	376.95	811.58	0.73	2.02	8.26	68.58	6.77
Annual average									
9:00 AM	473.16	3.02	429.24	1562.80	1.03	2.74	8.69	49.42	5.09
10:00 AM	720.58	4.57	490.45	2695.78	1.30	3.32	9.78	34.14	3.96
11:00 AM	860.91	5.77	513.07	3529.91	1.49	3.72	10.74	29.77	3.76
12:00 PM	943.91	6.36	534.99	4018.68	1.50	3.74	11.21	25.58	3.39
1:00 PM	923.72	6.17	527.23	3849.65	1.54	3.80	10.98	27.13	3.55
2:00 PM	868.97	5.78	507.28	3474.25	1.44	3.59	10.53	28.80	3.58
3:00 PM	770.75	5.02	492.12	2932.57	1.29	3.32	10.01	31.60	3.75
4:00 PM	611.12	3.93	461.80	2168.61	1.13	2.97	9.37	37.92	4.20
5:00 PM	407.92	2.62	420.91	1341.39	0.95	2.57	8.62	55.34	5.71

diesel/year, and as burning of 1 L diesel release about 3 kg CO_2, it will release 336 kg of CO_2 to the atmosphere. So, solar pump may not harm the atmosphere and will reduce our dependency on grid power or diesel for

Table 2 : Economics of Solar photovoltaic pump, Electric pump and Diesel pump.

(1)	**Operating cost of Solar photovoltaic Pump System (5 hp)**				
(1)	**Cost of PV System**	**Amount (`)**	**(2)**	**AC Water pump with controller**	**Amount (`)**
(A)	**Fixed Cost**		**(A)**	**Fixed Cost**	
	(i) Depreciation (D) /year	6660	(i)	Depreciation (D)/ year	3672
	(ii) Interest (I)/ year	12210	(ii)	Interest (I)/ year	2692.8
	Total Fixed Cost per year	18870		Total Fixed Cost per year	6364.8
	Total Fixed Cost per hour (A)	**18.87**		**Total Fixed Cost per hour (B)**	6.3648
(B)	**Variable Cost**		**(B)**	**Variable Cost**	
	(i) Repair and maintenance cost/hour	0.925	(i)	Repair and maintenance cost/hour	2.04
	(ii) Wages of operator / hour	45		**Total variable cost per hour (B)**	2.04
	Total variable cost per hour (B)	45.92		**Total Operating Cost of pump (A+B)**	**8.40**
	Total Operating Cost of PV system (A+B)	**64.79**			

Total Operating Cost of Solar Photovoltaic Pump is (1+2) = 73.19

Consideration: Capital cost of PV system (1.85 lac), Capital cost of AC pump with controller (0.408 lac), Salvage value-10% of depreciation cost, Useful life of the PV system (25 years), useful life of AC pump (10 years), interest rate (10%), annual working hours (1000), operator wages (‘360/day), maintenance cost of PV system (0.5% of total capital cost), maintenance cost of AC pump with controller (5% of total capital cost)

(2)	**Operating cost of Electric Water Pump (5 hp)**		**(3)**	**Operating cost of Diesel Pump (5 hp)**	
(A)	**Fixed Cost**	**Amount (`)**	**(A)**	**Annual Fixed Cost**	**Amount (`)**
	(i) Depreciation (D) /hour	1.665		(i) Depreciation (D) / hour	1.35
	(ii) Interest (I)/ hour	1.221		(ii) Interest (I)/ hour	0.99
	Total Fixed Cost / hour (A)	**2.886**		**Total Fixed Cost / hour (A)**	**2.34**
(B)	**Variable Cost**		**(B)**	**Variable Cost**	
	(i) Energy consumption (kWh) Energy cost per hr	7.61 30.45		(i) Cost of fuel per hour (ii) Lubricant per hour	179.8393 1.6785
	(i) Repair and maintenance cost/hour	1.85		(iii) Repair and maintenance cost/hour	1.5
	(ii) Wages of operator / hour	45		(iv) Operator's wages per hour	45
	Total variable cost/hour (B)	**77.30**		**Total variable cost (B)**	228.02
	Total Operating Cost of electric pump per hour (A+B)	**80.18**		**Total operating cost of diesel pump per hour (A+B)**	**230.36**

Consideration: Capital cost (0.18 lakh), Salvage value -10% of depreciation cost, Efficiency of motor and pump (70%), Useful life of the electric pump (10 years), interest rate (10%), annual working hours (1000), operator wages (‘360/day), Energy cost (‘4/kWH), maintenance cost (5% of total capital cost)

Consideration: Capital cost (0.15 lakh), Salvage value-10% of depreciation cost, Efficiency of diesel engine (40%), Efficiency of pump (70%), Diesel cost (‘ 90/lit), Useful life of pump (10 years), interest rate (10%), annual working hours (1000), operator wages (‘360/day), maintenance cost (5% of total capital cost)

irrigating our field. Price of the fossil fuel will increase in future whereas, the cost of the photovoltaic cell may reduce. In that case solar power-based pumping system may be more cost effective and more common in water pumping application.

Conclusion

Using a 5 HP AC pump powered by 20 solar panels, solar radiation, ranging from 257.53 to 1050.09 W/m², significantly impacted power generation, with an average panel output of 811.58 to 4532.79 W, peaking during the *Rabi* season. Water horsepower (WHP) varied between

0.73 and 1.72 HP, with peak efficiency observed around noon. Pump discharge rates, ranging from 2.02 to 4.18 liters per second (lps), directly correlated to solar irradiance. Efficiency metrics showed array efficiency of 8.26% to 11.64%, pump efficiency of 25.30% to 68.58%, and total system efficiency between 3.19% and 6.77%, with better performance in the morning due to lower pumping head. Economically, the solar pump's operating cost of ` 73.19/hour was lower than electric (` 80.18/hour) and diesel pumps (` 230.36/hour), demonstrating its cost-effectiveness. Additionally, solar pumps offer significant environmental benefits by reducing dependence on diesel and electricity, thus cutting greenhouse gas emissions. The study concludes that solar PV pumps are a viable solution for addressing water and energy challenges in agriculture, particularly in semi-arid regions, with optimal operation between 10 am and 4 pm for maximum water and energy efficiency.

References

Elnozahy, A., Abdel-Salam M. and Abo-Elyousr F.K. (2024). Optimal techno-economic energy coordination of solar PV water pumping irrigation systems. *Energy*, **288**, 129817.

Hilarydoss, S. (2023). Suitability, sizing, economics, environmental impacts and limitations of solar photovoltaic water pumping system for groundwater irrigation—a brief review. *Environ. Sci. Poll. Res.*, **30(28)**, 71491-71510. 7

Habib, S., Liu H., Tamoor M., Zaka M.A., Jia Y., Hussien A.G. and Kamel S. (2023). Technical modelling of solar photovoltaic water pumping system and evaluation of system performance and their socio-economic impact. *Heliyon*, **9(5)**.

Lal, S., Kumar P. and Rajora R. (2013). Performance analysis of photovoltaic based submersible water pump. *Int. J. Engg Technol. (IJET)*, **5(2)**.

Mokeddem, A., Midoun A., Kadri D., Hiadsi S. and Raja I.A. (2011). Performance of a directly-coupled PV water pumping system. *Energy Conversion and Management*, **52(10)**, 3089-3095.

Odeh, I., Yohanis Y.G. and Norton B. (2006). Economic viability of photovoltaic water pumping systems. *Solar Energy*, **80(7)**, 850-860.

Verma, S., Mishra S., Chowdhury S., Gaur A., Mohapatra S., Soni A. and Verma P. (2021). Solar PV powered water pumping system–A review. *Materials Today: Proceedings*, **46**, 5601-5606.