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ARTICLE

Design and Economic Evaluation of Grid-Connected PV Water Pumping Systems for Various Head Locations

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ABSTRACT: This research investigates the design and optimization of a photovoltaic (PV) water pumping system to address seasonal water demands across five locations with varying elevation heads. The system draws water from a deep well with a static water level of 30 m and a dynamic level of 50 m, serving agricultural and livestock needs. The objective of this study is to accurately size a PV system that balances energy generation and demand while minimizing grid dependency. Meanwhile, the study presents a comprehensive methodology to calculate flow rates, pumping power, daily energy consumption, and system capacity. Therefore, the PV system rating, energy output, and economic performance were evaluated using metrics such as discounted payback period (DPP), net present value (NPV), and sensitivity analysis. The results show that a 2.74 kWp PV system is optimal, producing 4767 kWh/year to meet the system's annual energy demand of 4686 kWh. In summer, energy demand peaks at 1532.7 kWh, while in winter, it drops to 692.1 kWh. Meanwhile, flow rates range from 11.71 m^3/h at 57 m head to 10.49 m^3/h at 70 m head, demonstrating the system's adaptability to diverse hydraulic conditions. Economic analysis reveals that at a 5% interest rate and an electricity price of $0.15/kWh, the NPV is $6981.82 with a DPP of 3.76 years. However, a 30% increase in electricity prices improves the NPV to $10,005.18 and shortens the DPP to 2.76 years, whereas a 20% interest rate reduces the NPV to $1038.79 and extends the DPP to 6.08 years. Nevertheless, the annual PV energy generation exceeds total energy demand by 81 kWh, reducing grid dependency and lowering electricity costs. Additionally, the PV system avoids approximately 3956.6 kg of CO_2 emissions annually, underscoring its environmental benefits over traditional pumping systems. As a result, this study highlights the economic and environmental viability of PV-powered water pumping systems, offering actionable insights for sustainable energy solutions in agriculture.

KEYWORDS: PV pumping; various head; grid dependency; net present value; payback period

1 Introduction

In the agricultural sector, particularly in regions where significant water volumes are required for irrigation, clean and sustainable energy sources are essential for operating water pumps. Nevertheless, global water systems are increasingly challenged by issues such as pollution, supply imbalances, and water scarcity. According to UNESCO, approximately 0.7 billion people across 43 countries currently face water shortages, and by 2025, two-thirds of the global population could be living under water stress [1].

To ensure the adequate delivery of water for both people and irrigation purposes, water pumps must be employed; however, these pumps require substantial energy. Therefore, solar-powered water pumping systems are becoming increasingly vital, especially in developing countries [2].

Solar powered irrigation systems will reduce the dependency on diesel generators and help reduce operation costs and environmental pollutants [3]. On the other hand, increasing global energy demand, along with continued reliance on energy generation from fossil fuels, is making climate change more severe and causing continued degradation of the environment [4]. The excessive use of fossil fuels results in pollution and very high greenhouse gas emissions [5]. This speeds up the global warming since extraction of these fossil fuels becomes scarier. The need, therefore, arises to shift towards renewable sources of energy production [6]. More countries hence adopt renewable energy technologies; governments of different countries are working towards finding a solution using solar energy, wind energy among others [7]. All such sources are clean and, therefore, represent an environmentally friendly alternative to fossil fuel-based pumps. PV systems increasingly address the demand for electricity, electrical network stability and low environmental impact. Solar PV systems have also come useful in supplying irrigation and, more importantly, drinking water, especially in places lying in the rural belt area. They support sustainable agriculture and better access to water [8]. Most the previous papers focused on the design methodology of an off-grid solar water-pumping system in order to decrease its dependence on diesel generators and can be deployed in places having no electricity. The various systems have already been effective for irrigation water supply in locations that have no access to electricity [9]. These depend on several studies to be made, including those dealing with the system's requirements and efficiency, the characteristics of the pump, and the solar radiation of the area. Thus, various research has focused on how different factors like pump head and water flow influence the demand for water [10–12]. The same is evident from the studies on seven different capacity solar water pumping systems (SWPS) installed at various locations in Wyoming, USA, by Chowdhury et al. [13]. It showed that SWPS is far more economically viable with a highly efficient operation for pumping water in faraway areas. Moreover, Whitfield et al. [14] investigated the pumping performance of a low-energy SWPS system, which has a power rating of 300 to 500 peak watts with a capacity of 40 m^3/day under a head of 10 m, to enhance customer satisfaction. Their results showed that the overall efficiency of the pump, motor, and controller system was between 40% and 60%–70% daily [15,16]. Further, other scholars have worked on the impact of complete dynamic head distribution and distributed solar radiation on the performance analysis of SWPS. They concluded their findings that systems designed for partial conditions gave the best performing at higher operating heads and higher amounts of insolation. An investigation by evaluated performance of SWPS sited in India [17]. The experimental results have exhibited an average daily water production of 38 m^3 at a flow rate range of 0.02 to 0.14 m^3/min, whereas an overall efficiency of the system is measured at 2.75%. Similarly, the investigation conducted in Tunisia [18] has discussed the effect of all the climatic variables on the performance of the 2.1 kW SWPS. It had computed the daily average water production as 7.7 m^3/day during the month of January and as 14.7 m^3/day for July. This amounts to an overall efficiency of the system of 3%. Another group of researchers [19] analyzed the efficiency of three SWPS systems and found that the systems could deliver 4–6 m^3 of water per day, with pump heads ranging from 19 to 35 m. The highest recorded system efficiency was 3%. Further, it was shown in a study on a 1.5 kW SWPS [20] that pumping speeds ranged from 6 to 65 L/min, operating for 6 to 8 h daily. Besides, an economic analysis of a 5.9 kW PV array-driven SWPS has been performed, which shows that the system can meet a daily water demand of 45 m^3 with a flow rate of 8 m^3/h at a head of 105 m [21]. In the study performed in Turkey, the feasibility of SWPS was discussed where unit water costs were given within the range of 0.24–0.26 USD/m^3 [22]. A comparison of SWPS systems in various configurations demonstrated that up to 22 m^3 of water could be supplied per day with a maximum pump head of 80 m, hence establishing the efficiency and adaptability of such systems under different conditions [23]. Electricity is predominantly used for operating water pumps to extract water from deep wells. These wells are typically located in low-lying areas; hence, water needs to be pumped up to a tank for gravity-fed irrigation. Conventionally, such pumps have been operated using grid electricity or diesel generators, which are costly and environmentally unfriendly. PV grid pumping systems reduce electricity costs by enabling farmers to generate their own electricity for irrigation while utilizing surplus power to offset costs. This approach reduces overall operating costs and effectively decreases dependence on the national grid, which has limited capacity to accommodate steadily increasing loads. Most of the existing literature focuses on the design of off-grid PV pumping systems. Meanwhile, this study emphasizes the sizing of a grid-connected PV pumping system tailored for applications where the grid has limited capacity and water demand is influenced by multiple-site hydraulic conditions. Therefore, it presents a comprehensive framework for integrating PV systems into grid-connected operations to balance energy demand and generation, ultimately achieving long-term economic benefits. The economic analysis, which includes DPP and NPV calculations alongside sensitivity analysis, provides ample insight into the financial viability of these systems. Meanwhile, the findings offer stakeholders a clear understanding of potential cost savings and the sustainability advantages of adopting grid-connected PV pumping systems in similar applications.

2 Methodology

The methodology adopted for this research underlines the technical and economic feasibility of solar-powered water pumping systems, taking into account that these are fitted to site requirements. This approach integrates hydraulic analysis, energy demand calculation, and PV system sizing, along with economic and sensitivity analyses that can be conducted to study performance and long-term viability. The methodology involves the following steps:

- Data Collection: Collecting information on water needs, PV generation, and pump specifications.
- Hydraulic Analysis: Determining the total head and flow rate at each location.
- Energy Demand Calculation: Using the hydraulic data to calculate the daily and seasonal energy demand for the pump system.
- PV Sizing: Determining the optimal PV size based on the energy demand and local solar radiation.
- Economic Analysis: Performing a cost-benefit analysis of the PV system by calculating the DPP and NPV.
- Sensitivity Analysis: Evaluating how changes in key variables, such as interest rates, energy costs, and electricity prices, impact NPV and DPP. This analysis assesses the long-term financial viability of solar-powered water pumping systems under varying economic conditions.
- Environmental Impact Analysis: Calculating CO_2 emissions reduction by comparing the carbon footprint of the solar PV-powered system with traditional grid-powered alternatives, thereby assessing its contribution to environmental sustainability.

2.1 Energy Calculation

The pumping system was to be serving several points at varying heads. The well is located in the valley, whereas the storage tanks are at high mountain areas. Variations of head exist depending on depth, location height, and distance to location. Hence, every location possesses its head and thus an altered flow rate by the pump. The flow rate through each head is related to performance characteristics of the pump and is generally given by a pump specification curve. The relationship between the head (H) and the corresponding flow rate (Q) is often linear, as described by Eq. (1).

$$Q(H) = (m \times H) + b \tag{1}$$

where:

Q (H): flow rate at a given head (m^3/h),

H: head (m),

m: slope of the pump's performance curve, representing how the flow rate decreases as the head increases,

b: intercept, indicating the maximum flow rate when the head is zero.

Constants m and b are determined based on the pump's specifications.

2.1.1 Power Calculation

The power at which water can be raised through a pumping system depends upon the head and related flow rate for any specific location. The head will determine how high the water has to be lifted while the flow rate is related to the rate of water flow through the system. The two factors form the basis for Eq. (2) in calculating the input pump power.

$$P = \frac{Q \times H \times \rho \times g}{\eta \times 1000} \tag{2}$$

where:

Q: flow rate in m^3/s (converted from m^3/h by dividing by 3600),

H: total head in meters,

ρ: water density (1000 kg/m^3),

g: gravitational acceleration (9.81 m/s^2),

η: pump efficiency (assumed to be 60%).

2.1.2 Pumping Duration

It will be directly proportional to the flow rate at any particular point and the daily demand for water. This time in hours can be calculated using the total amount of water needed per day in m^3 divided by the flow rate of the pump at a particular location in m^3/h. The following calculation will yield the number of hours per day the pump needs to be on in every location to satisfy the demand given by Eq. (3).

$$D = \frac{\text{Flow Rate}\,(m^3/h)}{\text{Water Need}\,(m^3/day)} \tag{3}$$

where:

D: time required to operate the pump (hours/day),

Water Need: the volume of water needed per day (m^3),

Flow Rate: the pump's flow rate at the corresponding head (m^3/h).

2.1.3 Determination of Daily Energy

The total energy required per day is the aggregate of the energy consumed by the pump across all locations. This is determined by multiplying the pump's power requirement at each location by the corresponding operational duration, and then summing the results for all locations, as expressed in Eq. (4).

$$E_{day\_total} = \sum_{i=1}^{n} P_i \times D_i \tag{4}$$

where:

P_i and D_i represent the power and duration for each location i.

2.2 PV Power Calculated

The PV power is calculated based on the energy required per day, the peak sunshine hours available per day, and the efficiency of the pump inverter as described in Eq. (5).

The equation to calculate the required PV power (P_{PV}) is:

$$P_{PV} = \frac{E_{day\_total}}{PSH \times \eta} \tag{5}$$

where:

P_{PV} is the required PV power (in kW),

E_{day_total} is the total energy required per day (in kWh),

PSH represents the peak sunshine hours per day (in hours),

η_{conv} is the efficiency of the conversion system (typically between 85% and 95%).

2.3 Economic Evaluation

An economic evaluation of the PV system configurations is conducted based on the following financial metrics.

2.3.1 Net Present Value

The NPV is a key financial metric that calculates the total value of an investment over its lifetime as in (6) [24], considering both the inflows (income from energy savings and outflows (initial investment and maintenance costs). The NPV considers the time value of money, meaning it discounts future cash flows to reflect their present value. A positive NPV indicates that the investment is profitable, while a negative NPV suggests not feasible.

$$NPV = \sum_{t=1}^{T} \frac{I_{annual}(t) - C_{annual}(t)}{(1+r)^t} - C_{initial} \tag{6}$$

where:

- I_{annual}: Annual income from energy savings in consumer bill,
- C_{annual}: Annual maintenance cost in year t, it includes expenses like cleaning and general upkeep of the PV system,
- $C_{initial}$: Initial investment cost of the PV system. This includes the cost of the PV panels, inverters, installation, and any other associated setup expenses,
- r: Discount rate,
- T: The time period over which the system is evaluated.

2.3.2 Discounted Payback Period

The DPP measures how long it takes for the cumulative discounted cash flows to recover the initial investment, accounting for the time value of money in (7) [24]. This factor provides a realistic assessment of how quickly the investment will pay off. Shorter DPP are generally more favorable.

$$\sum_{t=1}^{DPP} \frac{I_{annual}(t) - C_{annual}(t)}{(1+r)^t} = C_{initial} \tag{7}$$

3 Case Study

This case study presents the design of a PV water pumping system to cover the seasonal water demands at five different locations. The locations have different elevation heads, which means that the total head and flow rate will differ. The main objective is to find the optimal size of the PV system and analyze the grid dependency and the economic viability of the system for a whole year. The five sites analyzed in this study are all realistic and varied, each with a dedicated water storage tank. Water is first pumped from the artesian well to these tanks sequentially, which in turn distribute the water through gravity-fed systems to meet the needs of the agricultural lands and animal farms. The storage tanks ensure the efficient satisfaction of the needs of each site with respect to water requirements, either for agriculture or livestock. The system goes on to operate in series, pumping one site with the amount of water demanded before switching to the other. This approach not only ensures that each site receives its required water demand but also does so in a way to optimize energy use and water distribution. Meanwhile, the operation in series minimizes unnecessary energy wastage by operation on the needs of a single site at a given time. Therefore, the well owner intends to integrate solar energy into the system in order to enhance the efficiency of the system and reduce further operational costs. By appropriately sizing the PV system to match the energy demands of the water pumping process with the energy generated by the PV array, the system will have significantly reduced dependency on grid electricity. This shift towards solar energy is a sustainable solution to reducing electricity costs and increasing energy independence.

- Water Source: The water is pumped from a deep well with a static water level of 30 m and a dynamic level of 50 m when the pump is operating.
- Pump Specifications: The pump has a head range of 32 to 115 m, with corresponding flow rates of 14 m^3/h at 32 m and 6.4 m^3/h at 115 m. The coefficients of the head-flow equation, as given in Eq. (8) and illustrated in linear curve shown in Fig. 1. The pump efficiency is assumed to be fixed at 60%.

$$Q(H) = -0.09157 \times H + 16.93 \tag{8}$$

where:

- H: total head in meters,
- Q(H): flow rate in m^3/h.

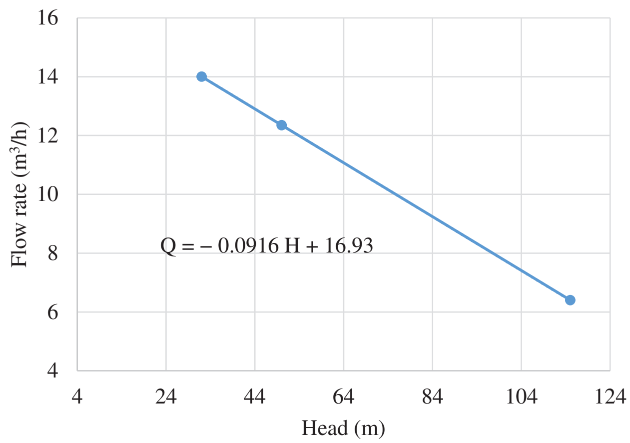

Figure 1: Head-flow rate pump curve

3.1 Locations Description

The system must deliver water to five locations, each with an additional head (due to elevation) and specific daily water demand. The total head at each location includes the dynamic level of the well (50 m) plus the additional head specific to each location. The pump's flow rate at each location depends on the total head, which in turn affects the power required for the pump as in Table 1.

Table 1: Head and flowrate of the locations

Location	Total head (m)	Flow rate (m^3/h)	Input power (kW)
Location 1	60	11.42	3.11
Location 2	62	11.23	3.17
Location 3	66	10.86	3.26
Location 4	70	10.49	3.34
Location 5	57	11.71	3.05

3.2 Seasonal Water Demand

Water demand varies seasonally, and the system is designed to handle seasonal water demands. The water need varies seasonally as in Table 2, with the highest demand in summer at 58.5 m^3/day and the lowest in winter at 27 m^3/day, with an average of 45 m^3/day throughout the year. The pump is expected to operate for different periods throughout the day depending on the season, with the daily energy consumption varying accordingly.

The seasonal water demand distribution, illustrated in Fig. 2, is expressed as percentages across the four seasons: Summer, Spring, Winter, and Autumn. As shown, water demand peaks in the summer, accounting for 32.5% of the total annual demand, which corresponds to the increased irrigation needs during the hotter months. In autumn, water demand decreases slightly to 27.5%, while spring experiences a moderate demand at 25%. The lowest water demand occurs during winter, constituting only 15% of the total. This seasonal variation emphasizes the need to align PV generation and pumping schedules, particularly during summer when both water demand and PV generation are at their highest. Therefore, ensuring the system's operational efficiency during this period is crucial for achieving optimal performance and meeting agricultural requirements effectively.

Table 2: Seasonal water demands of the locations

Location	Summer (m^3/day)	Spring (m^3/day)	Winter (m^3/day)	Autumn (m^3/day)	Average (m^3/day)
Location 1	13	10	6	11	10
Location 2	10.4	8	4.8	8.8	8
Location 3	15.6	12	7.2	13.2	12
Location 4	7.8	6	3.6	6.6	6
Location 5	11.7	9	5.4	9.9	9
Total	**58.5**	**45**	**27**	**49.5**	**45**

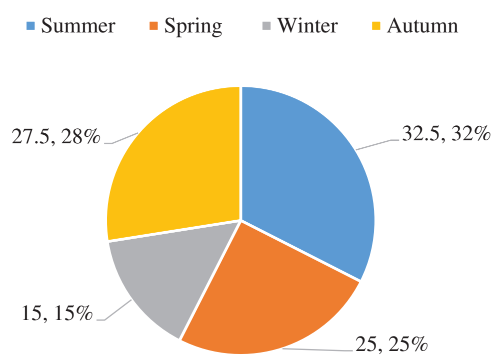

Figure 2: Seasonal water demand

The determination of the time required to meet the water demand can be calculated using Eq. (3), where the water demand is divided by the flow rate. Table 3 presents the calculated time required for the pump to lift the necessary water for each location. By combining the power values from Table 2 with the time values from Table 3, the total energy consumption is determined. This results in a total daily energy consumption of 12.84 kWh and an annual consumption of 4686 kWh.

Table 3: Daily and annual energy generation across different locations

Location	hours/day	Energy (kWh/day)	Energy (kWh/year)
Location 1	0.88	2.72	994.00
Location 2	0.71	2.26	824.26
Location 3	1.10	3.60	1314.81
Location 4	0.57	1.91	697.29
Location 5	0.77	2.34	855.61
Total	**4.03**	**12.84**	**4686**

3.3 Sizing PV Generator

The solar energy potential in Palestine is highly promising due to its sunny climate, with annual outputs estimated between 1700 and 1800 kWh/kWp and more than 3000 h of sunshine per year [25]. As shown in Fig. 3, this potential becomes even more evident when analyzing the daily solar radiation and temperature patterns throughout the year. Meanwhile, the solar radiation levels exhibit a pronounced seasonal variation, with the highest daily solar radiation occurring in the summer months. For instance, June experiences peak solar radiation of 7.79 kWh/m^2/day, making it the most optimal time for PV energy generation. Similarly, May, July, and August also show high solar radiation values, exceeding 7 kWh/m^2/day, which emphasizes the region's suitability for harnessing solar power during this period. Conversely, the winter months, particularly December and January, record the lowest daily solar radiation, at 2.49 and 2.71 kWh/m^2/day, respectively [25].

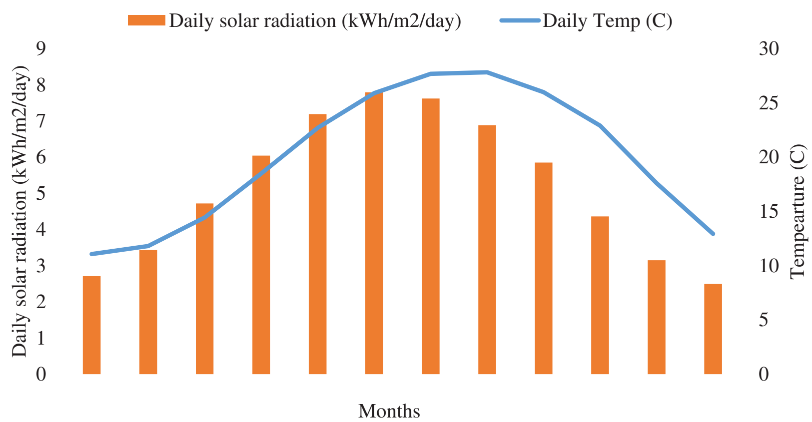

Figure 3: Location solar energy potential and temperature

Moreover, the daily temperature plays a crucial role in influencing PV system performance, as excessive heat can reduce the efficiency [25]. Throughout the year, the temperature ranges from a cool 11°C in January to a peak of 27.8°C in August. Therefore, the moderate temperatures in the spring and autumn months—ranging from 18.5°C in April to 26°C in September—are particularly favorable for maintaining high PV efficiency, as systems typically operate best in cooler conditions. In addition, the temperature data aligns well with the solar radiation levels, particularly in the months between March and October, where both factors combine to create ideal conditions for sustained solar energy production.

On the other hand, during the colder months (November to February), while the solar radiation is lower, the moderate temperatures reduce the likelihood of overheating in PV systems, ensuring stable, albeit reduced, performance. Therefore, the balance between temperature and solar radiation throughout the year ensures that PV installations would perform effectively, with minimal seasonal interruptions.

The required PV capacity can be calculated based on Eq. (5), where the rated power depends on the energy required per day, peak sunshine hours, and inverter efficiency.

$$P_{pv} = \frac{12.84}{5.2 \times 0.9} = 2.74\,\text{kWp}$$

The schematic diagram of the PV pumping system is shown in Fig. 4. The PV generator consists of 16 modules connected in series, with each module rated at 170 watts. These modules are connected to ensure compatibility with the inverter. The pump is positioned behind the meter, enabling the meter to operate bidirectional, importing energy when PV generation is lower than the power required by the pump, and exporting excess power to the grid when PV generation exceeds the pump's power demand.

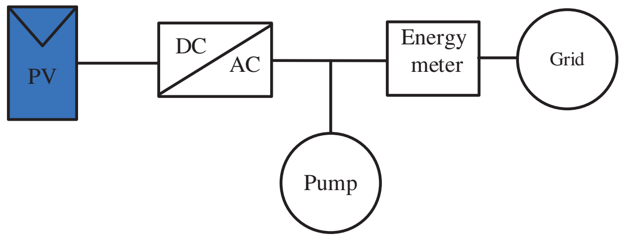

Figure 4: PV pumping grid connected system

The monthly energy production from the PV system shown in Fig. 5. As depicted, the summer months—June, July, and August—exhibit higher energy output, making the system particularly well-suited for a pumping application, as the energy demand for the pump is highest in the summer and lower in the winter. This correlation between the pump's energy requirements and PV power generation, which is moderate in spring and autumn, enhances the system's efficiency. The PV system is expected to generate a total of 4767 kWh annually, with an annual yield of 1702 kWh/kWp.

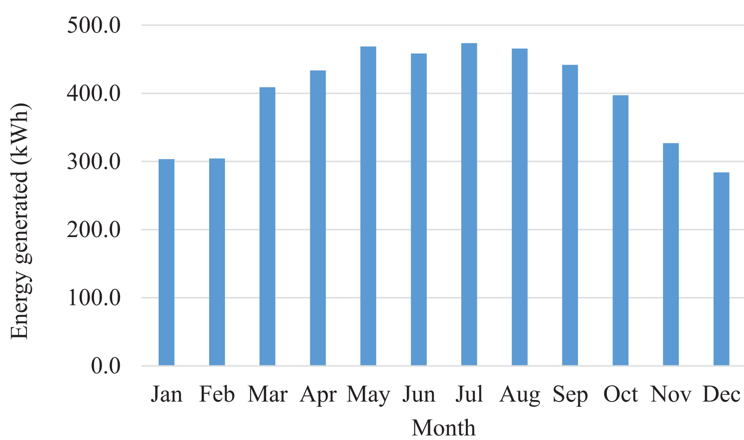

Figure 5: Monthly PV energy production

3.4 Grid Dependency

Grid dependency refers to the reliance of a system on electricity supplied by the grid, especially when renewable energy generation, such as from a PV system, is insufficient to meet demand. In this case study, the PV system's energy generation is compared with the seasonal energy requirements across summer, spring, winter, and autumn. The results, as shown in Fig. 6, reveal that grid dependency fluctuates throughout the year. In summer, the energy demand exceeds PV generation, creating a deficit of 134.85 kWh, which must be drawn from the grid. Meanwhile, in spring and winter, the system produces more energy than needed, with surpluses of 132.85 and 199.73 kWh, respectively. Therefore, the system operates independently from the grid during these seasons, even having the potential to export excess energy. Although autumn shows a slight shortfall of 116.34 kWh, it indicates only partial grid dependency during this period.

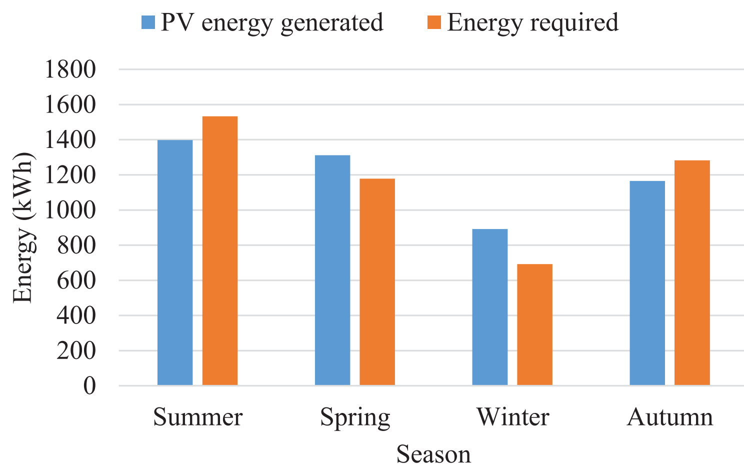

Figure 6: Seasonal energy production and energy required

The annual PV energy generation is 4767 kWh, while the energy required by the system is 4686 kWh, resulting in a surplus of 81 kWh annually. Nevertheless, this surplus plays a critical role during lower-demand periods such as spring and winter by reducing the need to import electricity from the grid, thereby enhancing both self-sufficiency and self-consumption. Meanwhile, during higher-demand periods like summer and autumn, the PV system significantly offsets grid dependency by reducing the burden on the grid and decreasing electricity costs.

The findings further highlight the seasonal fluctuations in energy production and demand. Summer and autumn represent periods of higher water demand, with energy requirements reaching 2814 kWh, accounting for 58.5% of the total annual demand. In contrast, winter and spring consume only 41.5% of the total energy. This higher demand during summer and autumn results in partial grid dependency, as the PV system alone cannot fully meet the increased energy needs.

Therefore, by alleviating grid dependency during high-demand months, the PV-powered system demonstrates its ability to support energy-efficient and cost-effective water pumping operations. Aligning the pumping operation with periods of high PV generation, as shown in Table 3, can further optimize energy usage and reduce electricity bills. This approach improves the economic feasibility of the system, making it particularly valuable for regions with significant seasonal variations in water needs.

4 Economic and Environmental Analysis

The economic analysis of the PV-powered water pumping system focuses on two key metrics: NPV and DPP. The initial investment for the system is approximately USD 800 per kilowatt, which includes the cost of solar panels, inverter, steel structure, and accessories. For a system size of 2.72 kW, the total investment amounts to USD 2176. Additionally, the annual maintenance cost is estimated at 3% of the initial investment, totaling USD 65.28 per year. The system generates annual savings by offsetting 4767 kWh of electricity costs at a rate of USD 0.15 per kWh, resulting in an annual income of USD 715.05. As illustrated in Fig. 7, the analysis considers a system lifetime of 25 years and an interest rate of 5%, providing valuable insights into the long-term financial viability of PV systems. This evaluation highlights the system's ability to achieve significant cost savings over its operational life, demonstrating its economic sustainability and attractiveness as a renewable energy investment.

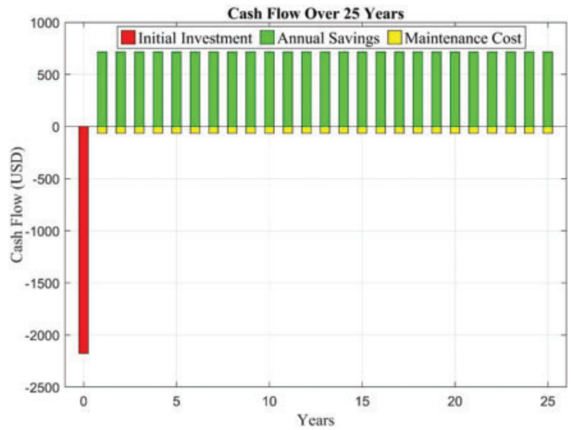

Figure 7: Cash flow analysis of PV pumping system

4.1 Net Present Value

The NPV is calculated to evaluate the financial return over the system's lifetime, accounting for the time value of money based in Eq. (6). The annual net savings, after deducting maintenance costs, are calculated as:

Annual net savings = 715.05 – 65.28 = 649.77 USD/year

Over the 25-year lifetime, and with a 5% discount rate, the NPV of the system is USD 6981.82. This positive NPV indicates that the PV system is financially beneficial over its lifetime, providing a return on investment significantly higher than the initial costs. The NPV calculation is crucial for stakeholders, as it measures the profitability of the investment, considering both savings and costs over time.

4.2 Discounted Payback Period

The DPP is the time it takes for the system to recover its initial investment through accumulated savings. The payback period for this PV system is calculated by dividing the initial investment by the annual net savings as in Eq. (7). This means that the system will take approximately 3.76 years to recover its initial costs as in Fig. 8. After the DPP, all subsequent savings contribute to additional financial returns. This relatively short payback period, combined with the positive NPV, demonstrates that the system is both cost-effective and sustainable in the long term.

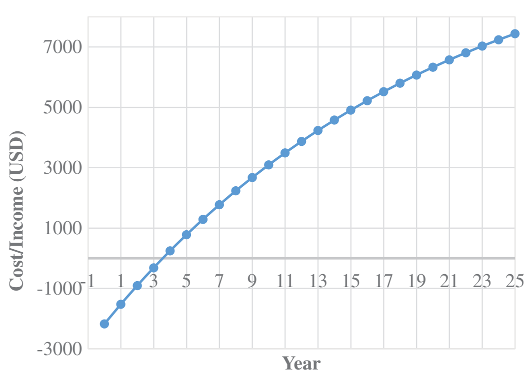

Figure 8: Cumulative annual cash flow

4.3 Sensitivity Analysis

The sensitivity analysis of the solar-powered water pumping system reveals significant trends in financial performance, particularly in terms of NPV and payback period, under varying interest rates. As shown in Fig. 9, higher interest rates substantially reduce the financial benefits of the system. For example, at an interest rate of 5%, the NPV is USD 6981.82, and the payback period is approximately 3.76 years. However, as the interest rate increases to 10%, the NPV decreases to USD 3721.90, and the payback period extends to 4.29 years. Further increases in the interest rate to 15% and 20% result in NPVs of USD 2024.21 and USD 1038.79, respectively, with payback periods extending to 4.99 and 6.08 years.

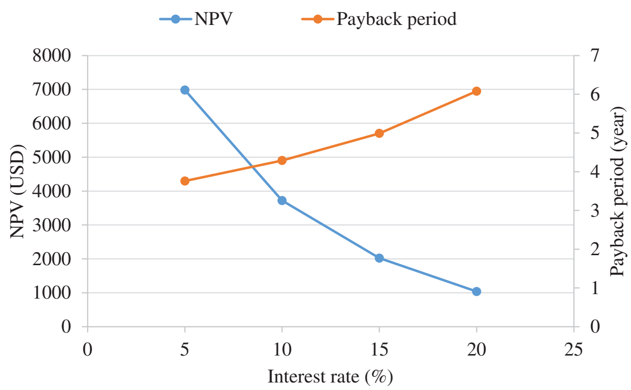

Figure 9: NPV and Payback period variations with interest rate

This trend illustrates that increased interest rates decrease the present value of future savings, which lowers the financial attractiveness of the system over time. Meanwhile, the analysis shows that as interest rates rise, the NPV significantly decreases with each incremental rise, while the payback period extends. This reflects a slower recovery of the initial investment and overall declining financial benefits. It follows that the financial performance of solar-powered water pumping systems is very sensitive to interest rates. The implication, therefore, is that for such systems to be more economically viable, interest rates will have to be considered by policymakers and investors if their growth is to be stimulated, especially in regions where renewable energy investments are vital for sustainable agricultural development.

The results of the sensitivity analysis, as illustrated in Fig. 10, evaluate the impact of rising electricity prices on the financial performance of the PV-powered water pumping system. The analysis reveals that increasing electricity prices significantly enhances the system's financial returns, as both the NPV and DPP improve with higher savings from offset electricity costs. For example, a 10% increase in electricity prices raises the NPV to USD 7989.61 and shortens the DPP to 3.36 years. A 15% increase further improves the NPV to USD 8493.50, with the DPP reduced to 3.18 years. With a 20% increase, the NPV reaches USD 8997.40, and the DPP decreases to 3.03 years. Meanwhile, a 30% increase in electricity prices results in the highest NPV of USD 10,005.18, with the DPP shortened to just 2.76 years. These findings demonstrate that rising electricity prices substantially enhance the financial viability of PV systems by increasing offset savings, making them a more attractive investment. Therefore, adopting PV-powered water pumping systems becomes increasingly advantageous in regions experiencing rising energy costs, reinforcing their role as a sustainable and cost-effective solution for agricultural operations.

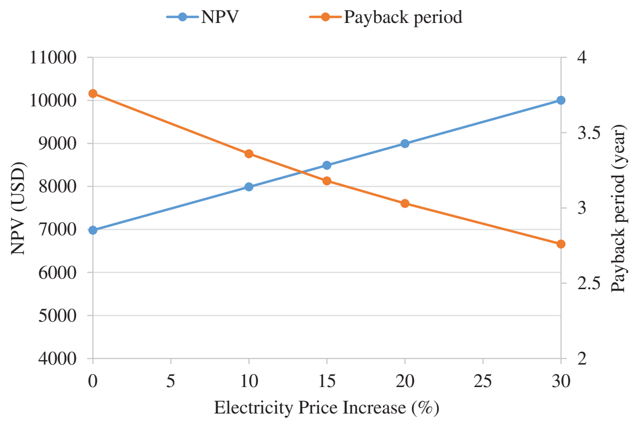

Figure 10: NPV and Payback period variations with electricity price

4.4 Environmental Benefits

The environmental benefits of the PV system are significant when compared to traditional pumping systems powered by grid electricity or diesel generators. Traditional energy sources contribute to greenhouse gas emissions, with an average CO_2 emission of approximately 0.83 kg per kWh of generated electricity [26]. By generating 4767 kWh annually, the PV system prevents the emission of approximately 3956.6 kg of CO_2 each year. This reduction in emissions highlights the potential for PV systems to mitigate the environmental impact of agricultural water pumping operations. Therefore, transitioning from conventional pumping systems to PV-powered systems not only addresses energy efficiency but also contributes to global efforts to combat climate change.

4.5 Policy Implication

The findings of this study provide valuable insights for policymakers to promote renewable energy adoption in agriculture. The demonstrated economic benefits of grid-connected PV pumping systems, including reduced electricity costs, lower grid dependency, and significant financial savings highlighted by favorable NPV and DPP results, underscore their potential as a sustainable solution. Meanwhile, these systems offer the dual advantage of supporting energy efficiency while mitigating environmental impacts, aligning with broader sustainability goals. Therefore, policymakers should consider integrating renewable energy objectives into agricultural development strategies to support the transition to sustainable farming practices. By encouraging the adoption of PV pumping systems, governments can enhance energy security, reduce grid dependency, and foster economic and environmental sustainability in agricultural operations.

5 Conclusion

This study successfully sized a PV-powered water pumping system to meet seasonal water demands across five locations with elevation heads ranging from 57 to 70 m. The hydraulic analysis revealed that flow rates varied between 11.71 and 10.49 m^3/h, depending on the head. The total annual energy consumption of the system was calculated to be 4686 kWh, with the highest demand observed during summer (1532.7 kWh) and the lowest during winter (692.1 kWh). The optimal PV system size was determined to be 2.74 kWp, capable of generating 1702 kWh/year per kWp. Sensitivity analysis highlighted the significant impact of financial variables on system performance. At an interest rate of 5% and an electricity price of USD 0.15/kWh, the NPV was USD 6981.82, with a DPP of 3.76 years. However, increasing the interest rate to 20% reduced the NPV to USD 1038.79 and extended the DPP to 6.08 years. Conversely, a 30% increase in electricity prices improved the NPV to USD 10,005.18 and shortened the DPP to 2.76 years, demonstrating the enhanced financial viability of PV systems under rising energy costs. In addition to financial benefits, the environmental advantages of the PV system are noteworthy. By offsetting 4767 kWh of electricity annually, the system prevents the emission of approximately 3956.6 kg of CO_2, contributing significantly to reducing the carbon footprint of agricultural operations. These findings emphasize the economic and environmental viability of integrating PV systems into water pumping applications, particularly in regions with increasing electricity costs and significant seasonal water demands. Therefore, policymakers and stakeholders should prioritize the adoption of PV systems to enhance energy independence, reduce grid dependency, and promote sustainable agricultural practices.

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References

1. Yokomatsu M, Ishiwata H, Sawada Y, Suzuki Y, Koike T, Naseer A, et al. A multi-sector multi-region economic growth model of drought and the value of water: a case study in Pakistan. Int J Disaster Risk Reduct. 2020;43:101368. doi:10.1016/j.ijdrr.2019.101368.
2. Saady I, Majout B, Adouairi MS, Karim M, Bossoufi B, Almalki MM, et al. Soft computing approaches for photovoltaic water pumping systems: a review. Clean Eng Technol. 2024;22(2):100800. doi:10.1016/j.clet.2024.100800.
3. Hilarydoss S. Suitability, sizing, economics, environmental impacts and limitations of solar photovoltaic water pumping system for groundwater irrigation—a brief review. Environ Sci Pollut Res. 2021;30(28):71491–510. doi:10.1007/s11356-021-12402-1.
4. Hassan Q, Viktor P, Al-Musawi TJ, Ali BM, Algburi S, Alzoubi HM, et al. The renewable energy role in the global energy transformations. Renew Energy Focus. 2024;48(12):100545. doi:10.1016/j.ref.2024.100545.
5. Ould-Amrouche S, Rekioua D, Hamidat A. Modelling photovoltaic water pumping systems and evaluation of their CO_2 emissions mitigation potential. Appl Energy. 2010;87(11):3451–9. doi:10.1016/j.apenergy.2010.05.021.
6. Kumar A, Kandpal TC. Potential and cost of CO_2 emissions mitigation by using solar photovoltaic pumps in India. Int J Sustain Energy. 2007;26(3):159–66. doi:10.1080/14786450701679332.
7. Osei Opoku EE, Acheampong AO, Dogah KE, Koomson I. Energy innovation investment and renewable energy in OECD countries. Energy Strategy Rev. 2024;54(4):101462. doi:10.1016/j.esr.2024.101462.
8. Dadhich G, Shrivastava V. Economic comparison of solar PV and diesel water pumping system. In: 2017 International Conference on Information, Communication, Instrumentation and Control (ICICIC); 2017; Indore, India. 416 p. doi:10.1109/icomicon.2017.8279156.
9. Chikh A, Chandra A. Optimization and control of a photovoltaic powered water pumping system. In: 2009 IEEE Electrical Power and Energy Conference (EPEC); 2009; Montreal, QC, Canada. p. 1–6. doi:10.1109/epec.2009.5420374.
10. Das BK, Hasan M, Rashid F. Optimal sizing of a grid-independent PV/diesel/pump-hydro hybrid system: a case study in Bangladesh. Sustain Energy Technol Assess. 2021;44(1):100997. doi:10.1016/j.seta.2021.100997.
11. Abid MZ, Yousif M, Ullah S, Hassan M. Design, sizing and economic feasibility of a hybrid PV/diesel/battery based water pumping system for farmland. Int J Green Energy. 2021;19(6):614–37. doi:10.1080/15435075.2021.1954007.

12. Vick BD, Neal BA. Analysis of off-grid hybrid wind turbine/solar PV water pumping systems. Sol Energy. 2012;86(5):1197–207. doi:10.1016/j.solener.2012.01.012.
13. Chowdhury BH, Ula S, Stokes K. Photovoltaic-powered water pumping: design and implementation—case studies in Wyoming. IEEE Trans Energy Convers. 1993;8(4):646–52. doi:10.1109/60.260976.
14. Whitfield GR, Burton JD. Increasing the cost-effectiveness of small solar photovoltaic pumping systems. Renew Energy. 1994;5(1–4):342–4. doi:10.1016/0960-1481(94)90394-8.
15. Odeh I, Yohanis YG, Norton B. Influence of pumping head, insolation and PV array size on PV water pumping system performance. Sol Energy. 2006;80(1):51–64. doi:10.1016/j.solener.2005.07.009.
16. Tiwari AK, Kalamkar VR. Effects of total head and solar radiation on the performance of solar water pumping system. Renew Energy. 2018;118(6):919–27. doi:10.1016/j.renene.2017.11.004.
17. Kolhe M, Joshi JC, Kothari DP. Performance analysis of a directly coupled photovoltaic water-pumping system. IEEE Trans Energy Convers. 2004;19(3):613–8. doi:10.1109/tec.2004.827032.
18. Hamrouni N, Jraidi M, Chérif A. Theoretical and experimental analysis of the behaviour of a photovoltaic pumping system. Sol Energy. 2009;83(8):1335–44. doi:10.1016/j.solener.2009.03.006.
19. Boutelhig A, Hadjarab A, Bakelli Y. Comparison study to select an optimum photovoltaic pumping system configuration upon experimental performance data of two different DC pumps tested at Ghardaïa site. Energy Proc. 2011;6:769–76. doi:10.1016/j.egypro.2011.05.087.
20. Mokeddem A, Midoun A, Kadri D, Hiadsi S, Raja IA. Performance of a directly-coupled PV water pumping system. Energy Convers Manag. 2011;52(10):3089–95. doi:10.1016/j.enconman.2011.04.024.
21. Al-Smairan M. Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: case study. Renew Sustain Energy Rev. 2012;16(7):4500–7. doi:10.1016/j.rser.2012.04.033.
22. Senol R. An analysis of solar energy and irrigation systems in Turkey. Energy Policy. 2012;47(3):478–86. doi:10.1016/j.enpol.2012.05.049.
23. Benghanem M, Daffallah KO, Alamri SN, Joraid AA. Effect of pumping head on solar water pumping system. Energy Convers Manag. 2014;77(6):334–9. doi:10.1016/j.enconman.2013.09.043.
24. Omar MA. Green mechanism: opportunities for corporate investment in PV/battery/diesel hybrid systems with techno-economic and environmental analysis. Energy Explor Exploit. 2024;42(6):2125–49. doi:10.1177/01445987241269009.
25. Omar MA, Mahmoud MM. Temperature impacts on the performance parameters of grid-connected PV systems based on field measurements in Palestine. IET Renew Power Gener. 2019;13(14):2541–8. doi:10.1049/iet-rpg.2018.6281.
26. Terang B, Baruah DC. Techno-economic and environmental assessment of solar photovoltaic, diesel, and electric water pumps for irrigation in Assam. India Energy Policy. 2023;183:113807. doi:10.1016/j.enpol.2023.113807.