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Techno Economic Analysis of Solar Powered Water Pumping Systems for Agriculture

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ABSTRACT

For agricultural irrigation, solar photovoltaic (PV) water pumping systems provide an alternative to diesel-powered pumping, especially in rural and off-grid areas where pumping operation may be impacted by fuel prices and electricity availability. The performance of a solar-powered water pumping system (SPWPS) and a diesel-powered water pumping system (DPWPS) for agricultural irrigation is compared in this study's techno-economic analysis. The research takes into account a 25-year project lifetime, an average peak solar hour of 5.2 hours per day, a daily water requirement of 60 m^3/day, and a total dynamic head of 45 m. While life cycle cost (LCC), levelized cost of water (LCOW), and simple payback period (PBP) were taken into account in the economic evaluation, technical sizing was carried out based on the necessary hydraulic energy and accessible solar resource. A 3.0 kWp PV array was chosen for the suggested system since the estimated hydraulic energy consumption was 7.36 kWh/day, which led to a necessary PV capacity of 2.83 kWp. The SPWPS produced an LCC of $8,740 and an LCOW of $0.037/$m^3$ during the course of the 25-year analysis period, while the DPWPS produced results of $19,120 and $0.108/$m^3$, respectively. The SPWPS has a simple payback period of 3.54 years. Additionally, a sensitivity analysis revealed that a 20% increase in diesel fuel prices shortened the SPWPS payback period to less than three years and raised the DPWPS LCOW to $0.130/$m^3$. These findings show that, given the study's assumptions, the suggested SPWPS can offer a technically and financially viable substitute for diesel-powered agricultural water pumping for the project's assessed lifetime.

1. Introduction

Agricultural irrigation requires a reliable supply of water and energy for pumping. In rural and off-grid agricultural areas, irrigation pumps may rely on diesel generators or conventional electricity, which can increase operating costs and dependence on fuel or grid availability [6]. Solar photovoltaic water pumping systems provide an alternative by converting solar radiation into electrical energy for

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operating irrigation pumps [3]. Recent research has also shown that photovoltaic-powered pumping systems may be assessed in terms of their technical performance, economic viability, and environmental impact in addition to energy conversion. Comparative techno-economic analyses of solar-powered water pumping options for irrigation applications have taken into account investment costs, operational costs, energy performance, and environmental consequences [12].

The application of solar-powered pumping is particularly relevant in agricultural areas with sufficient solar radiation and limited access to reliable electricity. Indonesian research has also investigated solar-powered pumping for agricultural irrigation, including applications in Madura and other agricultural areas [1]. The availability of solar resources and the pumping system's operating characteristics also affect how suitable solar-powered pumping is for agricultural applications. The link between solar irradiation, pump discharge, and system performance has been investigated in field tests of photovoltaic agricultural pumps, highlighting the significance of coordinating pump operation with available solar energy [7]. The performance of a solar-powered water pumping system is strongly affected by the hydraulic requirements of the application. Daily water demand, total dynamic head, solar radiation, pump efficiency, and PV capacity are important parameters in determining system performance [3]. Total dynamic head is particularly important because an increase in pumping head increases the energy required to deliver a given volume of water. A recent study demonstrated that changes in system head and solar radiation directly affect PV capacity, water discharge, life cycle cost, and the unit cost of pumped water [9]. Therefore, PV system sizing should consider both the required water volume and the available solar energy. System configuration can affect photovoltaic water pumping's dependability and cost-effectiveness in addition to hydraulic and solar resource conditions. In order to reconcile water pumping requirements with fluctuations in solar energy availability, recent optimization studies have looked at the coordination of photovoltaic power with energy storage. These methods show that when storage-based setups are used, PV capacity and storage capacity must be taken into account simultaneously [13].

Technical analysis alone is not sufficient to determine the feasibility of a solar-powered irrigation system. Economic assessment is required to evaluate the initial investment and the costs incurred during system operation. Recent studies have used life cycle cost analysis to compare different PV water pumping configurations and irrigation applications [8]. Other research has compared solar PV, diesel, and electric pumping systems by considering investment, operating costs, and environmental impacts [14]. These studies show that the economic performance of solar pumping depends on capital cost, fuel price, maintenance requirements, system lifetime, and local operating conditions. Because high initial investment and ongoing running costs might affect the accessibility and long-term adoption of pumping technologies, the economic evaluation of solar pumping is especially pertinent from the standpoint of agricultural users. Water storage can also be incorporated into a solar-powered pumping system to accommodate the difference between solar energy availability and irrigation demand. A storage tank allows water to be pumped during periods of available solar radiation and used later according to agricultural requirements [4]. This approach can reduce the need for chemical battery storage because water itself is stored as a useful form of energy. Recent research has examined solar irrigation systems with water storage and techno-economic optimization to improve the reliability and economic performance of agricultural pumping [4]. The long-term viability of solar water pumping systems may depend on institutional backing, professional expertise, operation, and maintenance in addition to the technological and financial aspects. Technical expertise, financial resources for technical assistance, and financial management were found to be significant factors linked to the requirement for post-construction support in Indonesian rural solar water-pumping systems.

The results show that in addition to the physical system design, technical and organizational capacity must be taken into account for community-scale solar pumping systems to be sustainable [11]. These results are supported by more comprehensive technological assessments, which demonstrate that the overall efficiency of freestanding photovoltaic pumping systems is significantly influenced by pump–motor design, power converter architecture, and control technique [5]. Further research on drip irrigation applications shows that energy management, water storage method, and system size are important factors in determining life cycle cost and water-use efficiency in solar-powered pumps [2]. Field-based system designs for smallholder farms in Sub-Saharan Africa also reveal that, in order to guarantee dependable daily water delivery for irrigation, pump and photovoltaic array characteristics must be appropriately matched to local solar resources and total dynamic head [reference missing; 10]

2. Methodology

The research methodology uses an integrated engineering and financial assessment model. System architecture and formatting guidelines for analytical visual aids are defined below.

Standardized scientific formatting is used for all schematic diagrams, performance curves, and comparative charts. The configuration and key elements of the proposed system are depicted in the schematic representations. The relationship between the pertinent technical parameters and system performance is shown using the performance curves. To clearly illustrate the variations in technical and financial performance of the assessed systems, comparative charts are offered.

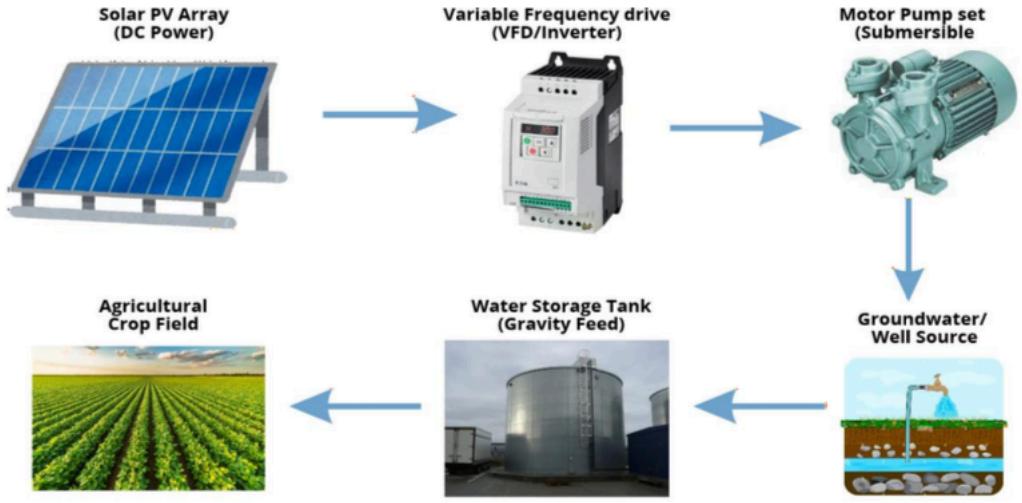


Fig. 1. Block Diagram of direct-coupled solar photovoltaic pumping system

The primary sizing inputs, operating assumptions, and comparison findings of the study are compiled in tables. The main factors used to calculate the necessary hydraulic energy and PV system capacity are shown in the sizing input tables. Information on system efficiency, sun availability, lifetime, and other analysis-related aspects is provided by the operational assumptions. The technical and financial performance of the solar-powered and diesel-powered water pumping systems are shown in comparison tables.

Table 1
Primary input parameters for technical design and financial evaluation

Parameter	Symbol	Value	Unit
Daily Water Demand	V	60.0	m^3/day
Total Dynamic Head	TDH	45.0	m
Average Peak Sun Hours	PSH	5.2	hours/day
Combined Pump-Motor Efficiency	ηpm	62.0	%
Controller/Inverter Efficiency	ηC	95.0	%
PV Derating Factor	Fd	85.0	%
System Lifetime	N	25	years
Discount Rate	r	8.0	%

2.1 Technical Hydraulic and PV Sizing

The daily hydraulic energy required (Eh) to deliver water volume V across the total dynamic head (TDH) is defined as:

$E_h = (\rho \times g \times V \times TDH) / (3.6 \times 10^6)$ (kWh/day)

2.2 Economic Evaluation Metrics

The total life cycle cost (LCC) accounts for initial capital expenditure (CAPEX), discounted operation and maintenance (O&M), component replacement (RC), and fuel costs (FC) over the project lifetime (N):

$LCC = CAPEX + \Sigma_{t=1}^{N} [(O\&M_t + RC_t + FC_t) / (1 + r)^t]$

The levelized cost of water (LCOW) measures the unit cost per cubic meter of water pumped:

$LCOW = LCC / \Sigma_{t=1}^{N} [Vannual / (1 + r)^t]$ ($/m^3$)

3. Results

The proposed equations are applied to a representative daily water demand of 60 m^3/day. The total dynamic head (TDH) considered in the calculation is 45 m. These parameters are used to determine the daily hydraulic energy required for the water pumping system. The calculated hydraulic energy requirement is then used to estimate the required photovoltaic (PV) array capacity. The results of these calculations are presented in the following equations and calculations.

Hydraulic Energy Requirement (E_h):

$E_h = (1000 \times 9.81 \times 60 \times 45) / (3.6 \times 10^6) = 7.36$ kWh/day

Required PV Array Size (P_{pv}):

$P_{pv} = 7.36 / (5.2 \times 0.95 \times 0.62 \times 0.85) = 2.83$ kWp

PV capacity chosen for this study is a system configuration based on the specified water demand, hydraulic head, solar resource, and overall system efficiency [12].

3.1 Economic Evaluation and Comparison

The financial performance of the solar-powered water pumping system is evaluated over a 25-year period. The analysis considers a 3.0 kWp Solar-Powered Water Pumping System (SPWPS) as the proposed system. Its financial performance is compared with an equivalent 4.5 kW diesel-powered

water pumping system. The comparison considers the initial investment, operating and maintenance costs, replacement costs, and overall life cycle cost of each system. The results of the 25-year financial performance comparison are presented in the following analysis and table.

Table 2
Illustrative 25-year life cycle cost comparison between SPWPS and DPWP

Currency	Metric / Financial Indicator	Solar PV System (SPWPS)	Diesel System (DPWPS)
$	CAPEX	6,800	2,200
$	Annual Fuel & O&M Expense	150	1,450
$	Inverter / Engine Replacement (t = 12)	900	1,800
$	LCC	8,740	19,120
	LCOW	0.037/m³	0.108/m³
	PBP	3.54 years	Baseline

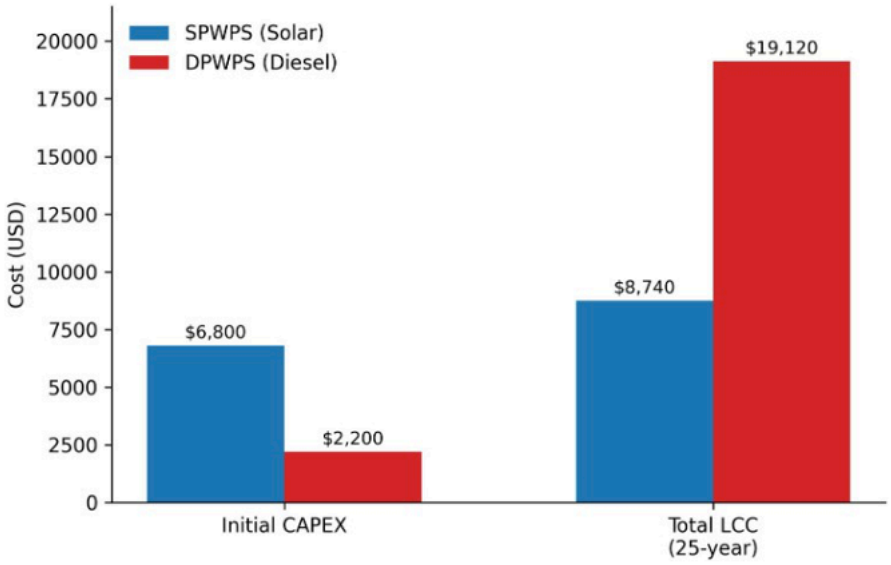


Fig. 2. CAPEX and 25-year total life cycle cost comparison between SPWPS and DPWPS (illustrative case)

These illustrative results are in line with recent field-based economic evaluations of solar lift irrigation, which found that a similar system used for smallholder paddy cultivation was significantly more cost-effective per unit of water delivered than diesel-based pumping while achieving a positive net present value, an internal rate of return above 20%, and a discounted payback period of less than six years under a high subsidy scenario [10]. In a similar vein, an assessment of solar-powered drip irrigation systems found that, in comparison to traditional diesel-powered options, these systems regularly offer lower operational costs and improved long-term financial sustainability despite higher upfront capital expenses [2].

The trade-off between a larger initial investment and lower ongoing running costs is demonstrated by the economic comparison. Although the SPWPS in this example case requires a larger initial capital investment than the DPWPS, the diesel system's yearly fuel and O&M costs are significantly higher. The lower life cycle cost and lower levelized cost of water obtained for the SPWPS are therefore a result of the difference in recurring expenditures. The economic performance of solar-powered water pumping systems has been found to be significantly influenced by capital cost,

operating expenditure, system efficiency, and project lifetime, according to similar techno-economic research [12].

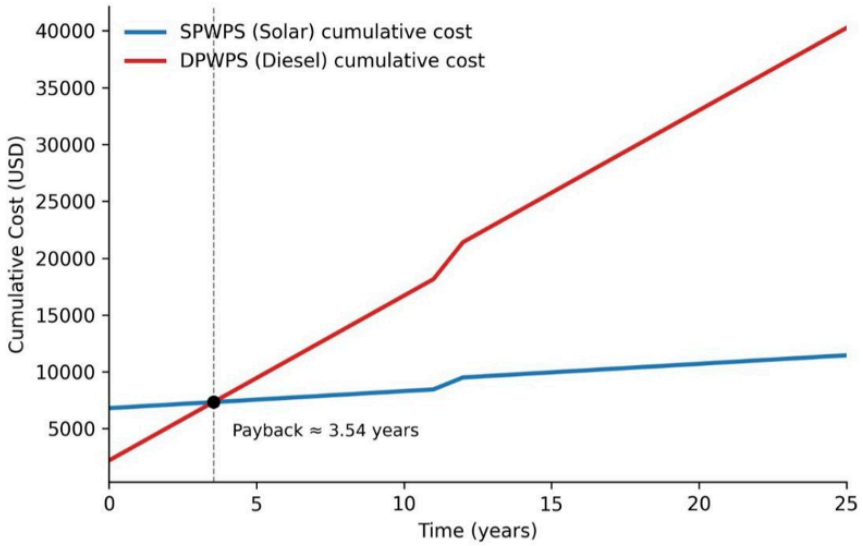


Fig. 3. Simple (undiscounted) cumulative cash outflow for SPWPS and DPWPS. Showing the crossover point corresponding to the simple payback period

Figure 3 shows the simple payback period using undiscounted cumulative cash outflow, which is different from the discounted LCC values shown in Table 2 and Figure 2; the crossover at roughly 3.54 years represents the point at which the additional upfront capital cost of SPWPS is offset by cumulative fuel and O&M savings. The difference between the original investment and the yearly operating expenses of the two systems is reflected in the computed simple payback period. The decrease in fuel and O&M costs throughout operation gradually offsets the SPWPS's comparatively larger initial investment. The financial performance of solar pumping has also been assessed through investment costs, operating savings, and payback-related indicators in earlier field-based research on solar lift irrigation; however, the final values are highly dependent on local system conditions, financing assumptions, and agricultural applications [10].

3.2 Sensitivity Analysis

● Sensitivity to Fuel Prices: The sensitivity analysis evaluates the effect of changes in diesel fuel prices on the economic performance of the water pumping systems. Diesel fuel prices are an important factor affecting the operating costs of the diesel-powered water pumping system (DPWPS). A 20% increase in global diesel prices is considered in this sensitivity analysis. This increase results in higher operating costs for the DPWPS over the analysis period. As a result, the levelized cost of water (LCOW) for the DPWPS increases to \$0.130/m³. Because fuel expenditure is a recurrent operational expense over the course of the system's lifespan, this sensitivity result shows that the economic performance of diesel-powered pumping is directly subject to fluctuations in fuel costs. Therefore, while assessing the long-term economic performance of diesel-based irrigation systems, fuel-price volatility should be taken into account. Techno-economic evaluations of water pumping systems, where variations in system costs and available solar resources affect the final cost of pumped water, also demonstrate the significance of operating-cost and resource-price assumptions [12].
The increase in the LCOW indicates that higher diesel fuel prices have a direct effect on the long-term operating cost of the DPWPS. In comparison, the solar-powered water pumping system (SPWPS) is

less affected by changes in diesel fuel prices because it does not require diesel fuel for normal operation. The increase in diesel prices also affects the economic comparison between the SPWPS and the DPWPS. Under the considered sensitivity scenario, the payback period of the SPWPS is reduced to less than 3.0 years. Therefore, the sensitivity analysis indicates that changes in diesel fuel prices can significantly influence the economic performance of the evaluated water pumping systems.

● Sensitivity to Solar CAPEX: The sensitivity analysis also considers the effect of changes in solar capital expenditure (CAPEX) on the economic performance of the SPWPS. The cost of photovoltaic (PV) modules is an important component of the initial investment in the solar-powered water pumping system. A decrease in PV module prices can reduce the total initial capital cost of the SPWPS. Lower capital costs can reduce the financial burden associated with the installation of the system. This condition can make the SPWPS more economically attractive for agricultural applications. The reduction in solar CAPEX can also improve the economic competitiveness of the SPWPS compared with the diesel-powered water pumping system. Lower initial investment requirements can reduce the financial barriers faced by smallholder farmers. This condition can make solar-powered water pumping systems more accessible to farmers with limited financial resources. The improvement in economic accessibility may also support wider adoption of solar-powered pumping systems in agricultural areas. Therefore, decreasing PV module prices can strengthen the economic feasibility and competitive position of the SPWPS. Because the photovoltaic array accounts for a significant amount of the initial expenditure, the sensitivity of solar pumping economics to PV component pricing is crucial. The capital requirement and consequent cost of pumped water may also be impacted by changes in PV module pricing. The sensitivity of water-discharge cost to PV module cost has been explicitly studied in recent techno-economic modeling, which has shown that changes in component pricing can affect the economic indicators of solar pumping systems [12].

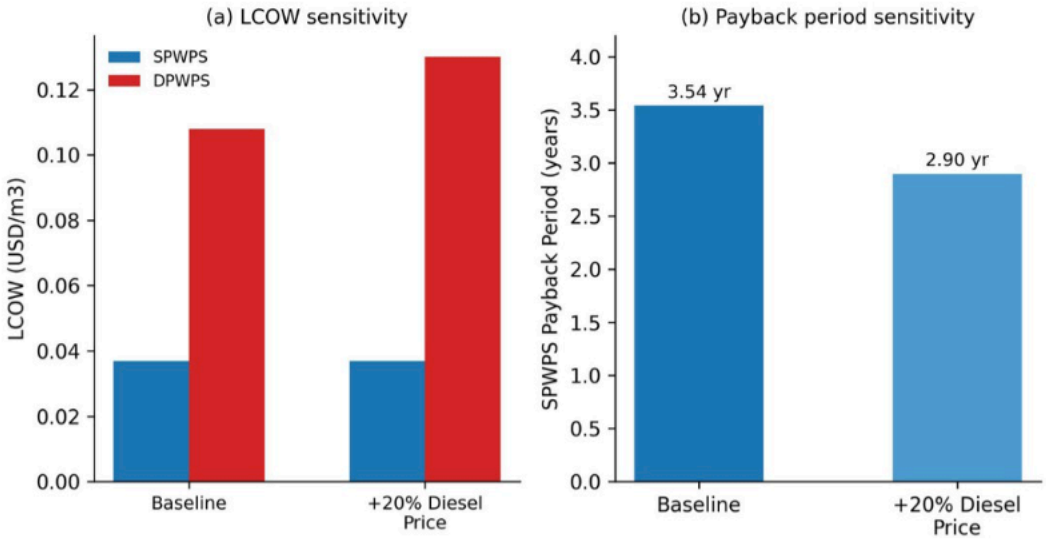


Fig. 4. Sensitivity of the Levelized Cost of Water (LCOW) to a 20% increase in diesel price (illustrative case)

4. Conclusions

The suggested 3.0 kWp Solar-Powered Water Pumping System (SPWPS) can supply the 60 m^3/day agricultural water demand at a total dynamic head of 45 m, according to the techno-economic analysis. The SPWPS obtained a lower life cycle cost of $8,740 and a lower levelized cost of water of

$0.037/m³ when compared to the evaluated Diesel-Powered Water Pumping System (DPWPS), which was $19,120 and $0.108/m³, respectively. Additionally, the SPWPS attained a simple payback period of 3.54 years. These results show that the SPWPS offers an economically viable and technically feasible substitute for agricultural water pumping under the study's assumptions. To assess the system under various site conditions, solar resources, water demands, and economic assumptions, more research is required.

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Conflict of Interest Statement
Regarding the publishing of this work, the authors state that they have no conflicts of interest. There was no funding, grants, or other compensation that would have affected the results of this investigation. The study was carried out without any financial or commercial ties that might be interpreted as a conflict of interest.

Statement of Author Contributions
Legison Satria Manik Allo helped with the manuscript's conception, methodology, technical analysis, economic analysis, data processing, and preparation. Thalita Rhea Amelia helped with the drafting of the text, data analysis, and result interpretation. Jalalludin Satriya Nayaka helped with technical analysis, paper revision, and data processing. Nadiya Ayu Astarini read the article, oversaw the research, and offered direction during the investigation. Each author read and approved the final version of the manuscript after contributing to its revision.

Statement of Data Availability
This article contains all of the data created or examined during this investigation. Upon reasonable request, the corresponding author can provide further details on the calculations and assumptions used in the analysis.

Ethics Statement
Animal subjects, human beings, or human biological materials were not used in this investigation. Thus, informed consent and ethical approval were not necessary.

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