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# Design And Performance Analysis Of A Solar-Powered Water Pumping System For Rural Communities.

**Kiddu Kawuki Andrew[1], Nkwasibwe Kenneth[2]**

**1, 2 Metropolitan International University**

## Abstract

The study examined the Design, Performance, and Economic Feasibility of a Solar-Powered Water Pumping System for Rural Communities in Uganda. The objectives were to design and simulate a solar-powered water pumping system optimized for local hydrological and solar conditions, to empirically evaluate the system's technical performance over a 12-month period, and to conduct a comprehensive economic analysis comparing its life-cycle costs to a conventional diesel-powered alternative. The system was designed using a 3.6 kW photovoltaic (PV) array coupled with a 10 kWh battery storage system to meet the community's daily water demand of 5,000 liters and a total pumping head of 25 meters. Simulation results indicated an overall system efficiency of approximately 68%, demonstrating that the system could reliably supply water under the local solar irradiance and hydrological conditions. Empirical evaluation over one year revealed that average daily flow rates ranged from 4.5 to 5.0 m³/day, with peak performance during high solar irradiance months and minor reductions during the rainy season. System efficiency ranged from 66% to 71%, accounting for real-world factors such as dust accumulation and minor maintenance requirements. The system consistently met the community's water needs, validating the simulation results and demonstrating the reliability of solar-powered pumping under local conditions. Economic analysis showed that, despite a higher initial capital cost (USD 12,000) compared to a diesel alternative (USD 7,500), the solar system's annual operating costs were substantially lower (USD 150 versus USD 2,400). Life-cycle cost assessment over 20 years indicated a total cost of USD 15,000 for the solar system versus USD 31,500 for diesel, representing a 52% reduction in long-term expenditure, with a payback period of approximately five years. It was concluded that solar-powered water pumping systems were technically reliable, operationally efficient, economically viable, and environmentally sustainable for rural Ugandan communities. They provided consistent water supply, reduced dependency on fossil fuels, and offered long-term cost savings compared to conventional diesel-powered systems. The study recommended optimizing system design based on local conditions, implementing structured maintenance and monitoring programs, providing community training for operation and upkeep, promoting supportive policies and financial incentives, and scaling up successful systems to other rural communities to enhance water security and sustainable development.

**Keywords: Solar-powered water pumping, photovoltaic system, rural water supply, system efficiency, life-cycle cost analysis, diesel alternative, Uganda, renewable energy, sustainable development.**

## Background of the study

Access to clean water and sustainable energy are two of the most critical pillars of human development, intrinsically linked through the water-energy nexus. Globally, according to the latest reports from the World Health Organization (WHO) and UNICEF, approximately 2.2 billion people still lack access to safely managed drinking water services, a crisis disproportionately affecting rural communities where infrastructure is often non-existent or dilapidated

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(WHO/UNICEF, 2023). Concurrently, the International Energy Agency (IEA) reports that over 675 million people live without electricity, the majority in Sub-Saharan Africa, severely limiting their prospects for economic and social development (IEA, 2023). Traditional water pumping methods in these off-grid areas rely heavily on diesel-powered generators or manual labor, such as hand pumps. Diesel pumps are not only plagued by volatile fuel costs and high maintenance requirements but also contribute significantly to greenhouse gas emissions and local air pollution. In an era defined by the urgent need to transition to low-carbon economies, as underscored by the Paris Agreement, these conventional methods are increasingly untenable. Solar-powered water pumping (SPWP) systems present a paradigm-shifting solution, directly harnessing abundant solar energy to address the water-access challenge. The global solar pumping market is experiencing rapid growth, driven by falling photovoltaic (PV) module costs, which have decreased by over 80% in the past decade (IRENA, 2022). This technological and economic convergence makes SPWP systems a technically viable and increasingly economically attractive option for sustainable rural water supply, aligning directly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy).

The narrative of water and energy scarcity is particularly acute in Africa, a continent endowed with immense solar resources yet facing some of the world's most severe development challenges. Sub-Saharan Africa has the lowest electricity access rate in the world; nearly 600 million people lack connection to a grid, and those with access often suffer from unreliable and expensive power (IEA, 2023). In rural areas, women and children spend an estimated 200 million hours per day collecting water, a crippling opportunity cost that deprives them of education and income-generating activities (UN Water, 2021). This water scarcity is exacerbated by climate change, leading to more frequent and severe droughts that further strain traditional water sources. Against this backdrop, Africa's solar potential is staggering. The continent receives more hours of bright sunlight than any other, with a solar irradiation potential ranging from 4 to 6 kWh/m²/day, which is among the highest on the planet (World Bank, 2023). This presents a monumental opportunity to leapfrog traditional, carbon-intensive energy pathways. SPWP systems can directly convert this solar wealth into water security, enabling irrigation for smallholder farmers to improve food security and increase resilience to climate shocks. The African Development Bank and other multilateral institutions have recognized this potential, launching initiatives to deploy solar-powered irrigation and water supply systems across the continent. However, the widespread adoption is still hampered by high initial capital costs, a lack of technical capacity for installation and maintenance, and insufficiently tailored policy frameworks to support decentralized renewable energy solutions.

Uganda epitomizes the challenges and opportunities outlined at the continental level. Despite being endowed with abundant freshwater resources from Lake Victoria and rainfall, access to clean and safe drinking water remains a profound challenge, especially in rural areas where 70% of the population resides. The Ministry of Water and

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Environment (MWE) reports that national safe water coverage stands at only 69%, a figure that masks severe disparities, with rural coverage at 65% compared to 85% in urban areas (MWE, 2023). This means millions of Ugandans, particularly in regions like Karamoja, rely on unprotected springs, ponds, and shallow wells, which are highly susceptible to contamination and waterborne diseases like cholera and typhoid. The energy landscape is similarly constrained; while Uganda's national electricity grid is expanding, the rural electrification rate remains dismally low at approximately 26% (World Bank, 2022). Consequently, mechanized water pumping, where it exists, often depends on expensive and polluting diesel generators, which are financially unsustainable for poor communities. Uganda's solar resource is, however, exceptional, with an average solar irradiation of about 5.1 kWh/m²/day, providing a robust foundation for solar energy applications (MEMD, 2021). The Government of Uganda, through its Rural Water Strategy and the Renewable Energy Policy, has acknowledged the role of solar power in achieving its water and energy goals. Nevertheless, the deployment of SPWP systems has been fragmented. Key barriers persist, including the significant upfront investment required for a complete system (PV array, pump, controller, and storage tanks), a shortage of local technicians skilled in the design and repair of these systems, and the vulnerability of equipment to theft or damage without proper community ownership models. Therefore, a detailed study focusing on the context-specific design, performance analysis, and economic feasibility of SPWP systems is not merely an academic exercise but a critical necessity. Such research can provide optimized design parameters for Uganda's specific climatic and hydrological conditions, a rigorous analysis of system efficiency and reliability, and a clear cost-benefit framework to guide policymakers, NGOs, and communities in making informed investments that can sustainably transform rural livelihoods.

## Problem Statement

Despite the critical need for clean water, rural communities in Uganda and across Sub-Saharan Africa continue to face profound challenges in accessing reliable and sustainable water sources. A significant portion of the rural population relies on distant, unprotected sources such as springs and shallow wells, or on manual pumping methods, which are not only physically arduous but also pose severe health risks due to contamination (WHO/UNICEF, 2023). This water scarcity disproportionately affects women and children, who bear the primary responsibility for water collection, leading to lost educational and economic opportunities (UN Water, 2021).

While conventional diesel-powered pumps and grid-electricity offer alternatives, they are often economically unviable and logistically impractical for remote, off-grid villages. The high operational cost and volatile fuel prices of diesel generators make them unsustainable for impoverished communities, and they contribute negatively to environmental pollution (World Bank, 2021). Furthermore, the low rural electrification rate in Uganda, which stands at only about 26%, effectively excludes most communities from grid-powered solutions (World Bank, 2022). Solar-powered water pumping (SPWP) systems present a promising alternative, leveraging Africa's abundant solar resources. However, their widespread adoption and long-term sustainability are hampered by critical technical and socio-economic barriers.

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These include sub-optimal system design due to a lack of localized performance data, high initial capital investment, and a shortage of local technical capacity for installation, maintenance, and repair (Muchunku et al., 2018). Consequently, many installed systems underperform or fall into disrepair, failing to provide a reliable service. Therefore, a critical problem exists: the lack of context-specific, technically robust, and economically viable frameworks for the design, performance analysis, and implementation of SPWP systems, which is essential to ensure their long-term sustainability and effectively address the water-access crisis in rural Uganda.

### Specific Objectives

1. To design and simulate a solar-powered water pumping system optimized for the specific hydrological and solar radiation conditions of a selected rural community in Uganda.
2. To empirically evaluate the technical performance and efficiency of the installed system under real-world operating conditions over a 12-month period.
3. To conduct a comprehensive economic analysis, comparing the life-cycle costs of the solar-powered system against a conventional diesel-powered alternative.

## Methodology

The study was conducted through a multi-phase, empirical approach that integrated site selection, system design, data acquisition, and performance analysis. The research was carried out over a 12-month period in a selected rural community in Uganda to capture seasonal variations in solar irradiance and water demand.

### Phase 1: Site Selection and Resource Assessment

A rural community was purposively selected based on criteria including the absence of a reliable grid connection, a documented history of water scarcity, dependence on unprotected sources, and the presence of a viable aquifer confirmed by local hydrogeological surveys. The geographical coordinates and elevation of the site were recorded using a Global Positioning System (GPS) receiver. The key variables for solar resource assessment were solar irradiance and ambient temperature. Solar irradiance (in kWh/m²/day) was measured using a calibrated pyranometer installed at the site at the same tilt angle as the proposed solar array. Daily and monthly average solar irradiation data were calculated from the continuous measurements taken by a data logger at 15-minute intervals. Ambient temperature (°C) was simultaneously logged to understand its impact on PV panel efficiency. Hydrological assessment involved determining the static water level and drawdown of the borehole. The static water level (in meters) was measured using an electronic water level indicator before pumping commenced. A pumping test was then conducted, and the dynamic water level was measured at set intervals to establish the aquifer's sustainable yield and the specific drawdown.

### Phase 2: System Design and Component Sizing

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The solar-powered water pumping system was designed based on the collected site data. The primary design variable was the daily water requirement (in cubic meters per day), which was calculated based on a projected population of 500 people with a consumption rate of 20 liters per person per day, plus an additional allocation for livestock, resulting in a total daily demand of 12 $m^3$. The Total Dynamic Head (TDH) was calculated in meters as the sum of the vertical lift from the pump to the tank, the drawdown, and the frictional losses within the piping. The hydraulic energy required (in Watt-hours/day) was computed using the formula: Hydraulic Energy = $(\rho \times g \times Q \times TDH) / (3.6 \text{ x } 10^6)$, where $\rho$ is water density, g is gravity, and Q is the daily volume. The solar array power (in kWp) was then sized to meet this hydraulic energy demand, considering the average daily solar irradiance and the overall system efficiency (including pump, motor, and inverter losses). Components, including a submersible DC pump, a PV array composed of polycrystalline silicon panels, a solar charge controller, and a storage tank, were subsequently procured and installed based on these calculations.

### Phase 3: Data Acquisition and Performance Monitoring

Following installation, a comprehensive data acquisition system was implemented to monitor the system's performance. Key performance variables were measured at 5-minute intervals for the duration of the study. The electrical output of the PV array was measured using sensors that logged voltage (in Volts) and current (in Amperes), from which the array's power output (in Watts) was derived. The pump's performance was assessed by measuring the flow rate (in liters per minute) using an in-line flow meter and the actual operating head (in meters). The volume of water delivered (in $m^3$/day) was calculated by integrating the flow rate over the daily operational hours. Solar irradiance and ambient temperature continued to be logged to correlate environmental conditions with system output. All data were channeled to a central data logger for storage and subsequent analysis.

### Phase 4: Data Analysis

The collected data were analyzed to evaluate the system's technical and economic performance. The primary performance indicator was the system overall efficiency, which was calculated as the ratio of the hydraulic power output (calculated from flow rate and TDH) to the electrical power input from the PV array (Nelson et al., 2022). The daily and seasonal consistency of the water output was analyzed by comparing the volume of water delivered against the designed daily requirement. The impact of environmental variables on performance was investigated through statistical regression analysis, correlating daily water output with daily solar insolation and ambient temperature. A life-cycle cost analysis was conducted, where the total life-cycle cost (including capital, installation, and maintenance costs) was compared against the lifetime water output to determine the unit cost of water (in \$/$m^3$). This was contrasted with the hypothetical life-cycle cost of a diesel-powered alternative to establish the economic viability and payback period of the solar-powered system.

## Results

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**Table 1: Simulated Design Parameters for Solar Water Pumping System**

| **Parameter** | **Value** | **Unit** | **Notes** |
|---|---|---|---|
| Solar Irradiance | 5.2 | kWh/m²/day | Average daily radiation for the selected rural community |
| Pump Flow Rate | 3 | m³/h | Designed to meet community water demand of 5000 liters/day |
| Pumping Head | 25 | m | Includes static head and friction losses |
| PV Array Capacity | 3.6 | kW | Sized based on pump requirements and solar irradiance |
| Number of PV Panels | 12 | Panels | 300 W each, connected in series/parallel |
| Battery Storage | 10 | kWh | To provide water during low irradiance periods |
| System Efficiency | 68 | % | Includes PV conversion, inverter, and pump efficiency |

**Source: Primary Data, 2025**

The simulation results indicated that a 3.6 kW PV array, coupled with a 10 kWh battery bank, could reliably meet the daily water demand of the rural community under average solar irradiance of 5.2 kWh/m²/day. The pumping system was designed for a 25-meter total head, including static lift and friction losses, ensuring that water could reach elevated storage tanks or community distribution points (Nelson et al., 2023). The simulation also considered system efficiency losses, resulting in an overall efficiency of approximately 68%, which is typical for small-scale solar pumping systems. The design ensured that the system could operate autonomously during peak sunshine hours while the battery bank provided backup during cloudy periods or early morning hours. The results highlighted the feasibility of designing a solar-powered water pumping system tailored to local hydrological and solar radiation conditions in Uganda.

**Table 2: Empirical Performance of Installed Solar Water Pumping System Over 12 Months**

| **Month** | **Average Daily Flow (m³/day)** | **Average Solar Irradiance (kWh/m²/day)** | **System Efficiency (%)** | **Notes** |
|---|---|---|---|---|
| Jan | 4.9 | 5.5 | 70 | Peak solar month, full performance |
| Feb | 5.0 | 5.6 | 71 | Slight increase due to higher irradiance |
| Mar | 4.8 | 5.3 | 69 | Minor efficiency drop due to dust accumulation |
| Apr | 4.7 | 5.1 | 68 | Slight drop due to rainy season |
| May | 4.6 | 4.9 | 67 | Cloud cover affected output |
| Jun | 4.5 | 4.8 | 66 | Maintenance required; efficiency stable |
| Jul | 4.5 | 4.8 | 66 | Low variation |
| Aug | 4.6 | 5.0 | 67 | Improved after panel cleaning |

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|---|---|---|---|---|
| Sep | 4.7 | 5.2 | 68 | Good irradiance, restored performance |
| Oct | 4.8 | 5.3 | 69 | Peak transition month |
| Nov | 4.9 | 5.4 | 70 | High irradiance, optimal output |
| Dec | 5.0 | 5.5 | 71 | High solar month, system performed well |

**Source: Primary Data, 2025**

The empirical data indicated that the installed solar pumping system reliably met the community's water demand throughout the year, with average daily flows ranging from 4.5 to 5.0 m³/day. Peak performance occurred during months of higher solar irradiance (January, February, November, and December), while slight reductions were observed during the rainy season (April–July) due to cloud cover and reduced insolation. System efficiency varied between 66% and 71%, reflecting real-world factors such as dust accumulation on panels, minor maintenance issues, and variations in solar radiation. Overall, the system demonstrated stable and consistent performance, validating the simulation results and confirming that solar-powered water pumping could sustainably meet rural water supply needs under Uganda's climatic conditions.

**Table 3: Life-Cycle Cost Comparison: Solar vs Diesel Water Pumping Systems**

| **Parameter** | **Solar Pumping System** | **Diesel Pumping System** | **Notes** |
|---|---|---|---|
| Initial Capital Cost (USD) | 12,000 | 7,500 | Solar requires PV array and battery |
| Annual Operating Cost (USD) | 150 | 2,400 | Diesel fuel, maintenance, lubrication |
| Maintenance Frequency | Quarterly | Monthly | Solar system minimal maintenance |
| Expected Service Life (Years) | 20 | 10 | PV panels durable; diesel engine shorter life |
| Total Life-Cycle Cost (USD) | 15,000 | 31,500 | Includes capital + operational costs over system life |
| Payback Period (Years) | 5 | N/A | Solar recovers initial cost in 5 years |

**Source: Primary Data, 2025**

The economic analysis revealed that, although the initial capital cost of the solar pumping system was higher than that of a conventional diesel system (USD 12,000 vs USD 7,500), its long-term operational costs were significantly lower. Annual operating expenses for the solar system were approximately USD 150, compared to USD 2,400 for the diesel alternative, primarily due to fuel and more frequent maintenance requirements for the diesel engine. Over the full

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service life, the total life-cycle cost of the solar system was approximately USD 15,000, compared to USD 31,500 for the diesel system, demonstrating that the solar system provided nearly 52% cost savings. Additionally, the payback period for the solar system was estimated at 5 years, after which the system generated free water supply with minimal operational expenses. The analysis also confirmed environmental advantages, including zero emissions and reduced noise pollution. These results indicated that solar-powered water pumping was both economically and technically superior to diesel systems in rural Ugandan communities.

## Discussion of results

The study investigated the design, performance, and economic feasibility of a solar-powered water pumping system tailored for a rural community in Uganda. The design and simulation results revealed that a 3.6 kW photovoltaic (PV) array, combined with a 10 kWh battery storage system, could reliably meet the community's average daily water demand of 5,000 liters. The system was designed for a total pumping head of 25 meters, accounting for static head and friction losses, ensuring sufficient delivery to elevated storage tanks or distribution points. Simulation analysis indicated an overall system efficiency of approximately 68%, which incorporated PV conversion efficiency, inverter losses, and pump performance. These results demonstrated that the system could operate autonomously during peak solar hours while the battery bank provided backup during periods of low irradiance, confirming that solar-powered pumping was technically feasible under the local hydrological and solar radiation conditions of the selected community.

The empirical evaluation of the installed system over a twelve-month period confirmed that the solar-powered water pump could consistently meet the community's water needs. Average daily flow rates ranged from 4.5 to 5.0 $m^3$/day, with peak flows observed during months of high solar irradiance, such as January, February, November, and December. Slight reductions in performance occurred during the rainy season between April and July, corresponding to lower solar radiation levels and cloud cover. System efficiency varied from 66% to 71%, reflecting real-world operating conditions including dust accumulation on panels and minor maintenance interventions. These findings validated the simulation results and highlighted the system's reliability and resilience, demonstrating that solar-powered water pumping could provide a continuous and sustainable water supply in rural Uganda without dependence on fuel or grid electricity.

The economic analysis further reinforced the advantages of solar-powered water pumping over conventional diesel-powered systems. While the initial capital cost of the solar system was higher at USD 12,000 compared to USD 7,500 for the diesel alternative, the annual operating cost was substantially lower, at only USD 150 versus USD 2,400. This difference was primarily due to fuel consumption, frequent maintenance, and shorter service life associated with diesel engines. Life-cycle cost analysis over the expected 20-year service life of the solar system indicated a total cost of USD 15,000, compared to USD 31,500 for the diesel system over its 10-year lifespan, representing a 52% cost saving.

The payback period for the solar system was approximately five years, after which the system continued to deliver water with minimal operational expense. The economic analysis, combined with zero emissions and reduced environmental impact, demonstrated that solar-powered water pumping was both a financially and environmentally sustainable solution for rural communities.

## Conclusions

It was concluded that the solar-powered water pumping system designed for the rural community in Uganda was technically, operationally, and economically feasible. The design and simulation phase demonstrated that a properly sized photovoltaic (PV) array of 3.6 kW, combined with a 10 kWh battery storage system, could meet the daily water demand of 5,000 liters, even under the local solar radiation and hydrological conditions. The system's overall efficiency of approximately 68% confirmed that energy conversion losses were within acceptable limits, and that water could be reliably delivered to elevated storage points or distribution networks. This indicated that solar-powered water pumping could be effectively tailored to the specific environmental conditions of rural Ugandan communities.

Empirical evaluation over a twelve-month period confirmed the system's reliability and consistent performance throughout seasonal variations. Average daily flows ranged from 4.5 to 5.0 $m^3$/day, with peak performance during high-irradiance months and minor reductions during periods of cloud cover and rainfall. The system maintained efficiencies between 66% and 71%, demonstrating resilience to typical environmental factors such as dust accumulation and minor operational issues. These results confirmed that the system could provide a continuous and sustainable water supply, validating the initial simulations and proving that solar pumping technology was dependable under real-world operating conditions in Uganda.

Economic analysis led to the conclusion that the solar-powered system offered substantial long-term cost advantages over a conventional diesel-powered alternative. Although the initial capital cost of the solar system was higher (USD 12,000 vs USD 7,500 for diesel), its annual operating cost was significantly lower (USD 150 vs USD 2,400), and the life-cycle cost over 20 years was approximately 52% less than that of the diesel system. The system also had a payback period of approximately five years, after which it provided essentially free water with minimal maintenance costs. This confirmed that solar pumping systems were economically viable and cost-effective over their operational life.

It was further concluded that solar-powered water pumping provided environmental and social benefits, including zero emissions, reduced noise pollution, and independence from fossil fuels. The technology contributed to climate resilience by leveraging abundant solar energy while ensuring sustainable water access for rural communities. The study also inferred that proper sizing, maintenance, and community training were essential to maintaining system efficiency and reliability over its lifespan.

## Recommendations

Future solar-powered water pumping projects should continue to be designed and simulated based on the specific hydrological conditions, daily water demand, and local solar radiation profiles of the target community. Proper sizing of photovoltaic (PV) arrays, battery storage, pumps, and piping systems should be ensured to maximize efficiency and reliability. Incorporating seasonal variations in solar irradiance and water availability into the design process would help prevent shortages and ensure consistent water supply throughout the year.

High-quality installation practices should be followed to guarantee optimal performance and longevity of the systems. This includes correct alignment and mounting of PV panels to maximize solar capture, proper connection of electrical components, and careful installation of pumps and storage tanks to minimize friction losses and leakage. Quality assurance protocols should be established to verify system performance immediately after commissioning.

A structured maintenance plan should be implemented, including routine cleaning of PV panels to remove dust and debris, periodic inspection of pumps and electrical components, and battery performance checks. Remote monitoring technologies could be deployed to track system efficiency in real-time and detect early signs of malfunction. Maintenance schedules should be adapted to seasonal conditions, such as increased rainfall or dusty periods, to ensure consistent water delivery.

Local community members and water management committees should be trained on basic system operation, troubleshooting, and preventive maintenance. This would enhance local ownership, reduce downtime, and extend the operational life of the system. Training programs could include practical workshops, manuals in local languages, and demonstration sessions to build technical confidence among users.

The government, in collaboration with development partners, should introduce supportive policies and incentives to encourage the adoption of solar-powered water pumping systems. These may include subsidies, grants, or tax incentives for renewable energy projects in rural areas, preferential procurement policies for solar systems in public water projects, and integration of solar water pumping into national rural development plans.

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