



OFF-GRID SOLAR PHOTOVOLTAIC PUMPING FOR SMALL-SCALE IRRIGATION IN SHANI, BORNO STATE

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ABSTRACT

This study evaluated the technical performance, hydraulic delivery reliability and economic viability of an off-grid solar photovoltaic (PV) pumping system against a conventional petrol pump. Six *fadama* farm sites were monitored from February to April during the dry season. Solar irradiance, PV output, discharge and dynamic total head were measured using a calibrated pyranometer, ultrasonic flow meter and piezometric pressure transducers. The 1.2 kWp PV system recorded a mean daily solar resource of 6.31 ± 0.42 kWh/m²/day, mean array efficiency of $14.2 \pm 0.6\%$ and mean performance ratio of 0.71 ± 0.04 . At 1,020 W/m², the system produced $1,120 \pm 32$ W of DC power, a dynamic head of 16.2 ± 0.9 m, a discharge of 5.20 ± 0.24 L/s and 826.4 W of hydraulic power. Over 10 years, the solar system had a life-cycle cost of \$2,070 compared with \$4,870 for the petrol pump; LCOE was \$0.112/kWh compared with \$0.418/kWh and LCOW was \$0.024/m³ compared with \$0.077/m³. Solar pumping also achieved 96.4% operational reliability and 82.1% irrigation conveyance efficiency. The findings indicate that appropriately sized solar PV pumping systems can provide a technically viable, economically competitive and reliable option for dry-season irrigation in Shani and comparable semi-arid environments.

Keywords: Dynamic, Head, Fadama, Irrigation, Solar PV, Pumping.

INTRODUCTION

The dry-season floodplain (**fadama**) agriculture of the Shani River and its seasonal tributaries in Shani Local Government Area, Borno State, is an important contributor to the local economy. High-value horticultural crops such as tomato (**Solanum lycopersicum**), onion, sweet pepper (**Capsicum annum**) and leafy vegetables are cultivated during the prolonged dry season from November to May. However, small-scale farming is constrained by limited access to suitable and affordable water-lifting systems from riverbanks, shallow tubewells and alluvial aquifers. Farmers along the Hawul River floodplain have traditionally used small-capacity petrol or diesel engine-driven centrifugal pumps. The study reported that energy accounted for 45–60% of seasonal production costs and that rising and erratic fuel and maintenance costs encouraged farmers to reduce irrigation application, contributing to water deficits and lower crop yield and quality.

Solar photovoltaic (PV) pumping provides a clean alternative because the dry-season period coincides with strong solar availability. The source study reported global horizontal irradiance in Shani of approximately 5.8–6.5 kWh/m²/day and noted that adoption has remained limited partly because of insufficient field evidence on system efficiency under varying pumping heads and economic performance relative to fossil-fuel pumps. Previous studies have shown that PV pumping performance depends on solar radiation, total system head and system losses. Akinyele and Olatomiwa (2022) reported that higher solar radiation improved PV pumping performance, while increasing total head constrained performance. Bawa *et al.* (2025) reported strong technical and economic performance for PV-powered drip irrigation in Ghana. Xie (2021) emphasized life-cycle costing when comparing solar and diesel irrigation because higher capital cost can be offset by lower recurring fuel and maintenance expenditure. Xie *et al.* (2024) also identified financing, technical skills, spare parts and after-sales services as important barriers to smallholder adoption.

Therefore, this study assessed the technical performance, hydraulic reliability and life-cycle economics of an off-grid stand-alone PV water-pumping system for smallholder **fadama** irrigation in Shani, Borno State, with emphasis on solar irradiance, dynamic head, discharge, PV array efficiency, performance ratio and long-term water-pumping costs.

MATERIALS AND METHODS

Study Area

Field research was conducted across six selected *fadama* farm clusters situated along the banks of the Shani River (Gwadinba), Shani, at latitude 09°14' N, longitude 11°42' E and an altitude of 340 m above sea level. The climate was semi-arid, with a dry season extending from October to May. Measurements were concentrated during February–April, when ambient temperatures reached 36–42°C and crop water demand was high.

Solar PV Pumping System

The experimental pumping unit consisted of a 1.2 kWp ground-mounted monocrystalline PV array comprising four 300 Wp panels connected in series-parallel, seasonally adjusted to a 12° south-facing tilt. The system included a maximum power point tracking (MPPT) solar pump controller/inverter and a DC brushless helical-rotor submersible pump installed in shallow tubewells or protected river-bank intake sumps.



Figure 1. Field setup of the solar PV pumping system

Instrumentation and Data Collection

Global horizontal irradiance was monitored continuously with a calibrated Kipp & Zonen CMP3 pyranometer connected to a data logger at 15-minute intervals. Pump discharge was measured using a non-invasive transit-time ultrasonic flow meter clamped to the high-density polyethylene delivery pipeline. Dynamic total head was calculated from static suction lift, drawdown measured using piezometric pressure transducers and friction losses along the 50 mm HDPE delivery pipe.

Technical Performance Analysis

Solar array efficiency was calculated using Eq. (1) (Duffie & Beckman, 2013; IEC, 2017):

$$\eta_{\text{array}} = [P_{\text{dc}} / (G \times A_{\text{array}})] \times 100 \quad (1)$$

where; P_{dc} is array DC electrical output (W), G is solar irradiance (W/m^2), and A_{array} is total array aperture area (m^2).

Hydraulic power output was determined using Eq. (2) (Masters, 2013):

$$P_{\text{hyd}} = \rho \times g \times Q \times H_{\text{td}} \quad (2)$$

where; ρ is water density ($1,000 \text{ kg}/\text{m}^3$), g is acceleration due to gravity ($9.81 \text{ m}/\text{s}^2$), Q is discharge rate (m^3/s), and H_{td} is total dynamic head (m).

System performance ratio (PR) was expressed using Eq. (3) (IEC, 2017):

$$PR = Y_f / Y_r \quad (3) \text{ where; } Y_f \text{ is final system yield (kWh/kWp) and } Y_r \text{ is reference solar yield (h).}$$

Economic Analysis

A 10-year financial assessment was conducted using a 10% annual discount rate and local fuel-price metrics. LCOE was calculated using Eq. (4) (Kuckshinrichs *et al.*, 2025):

$$LCOE = [C_{\text{init}} + \sum (OM_t / (1 + r)^t)] / [\sum (E_t / (1 + r)^t)] \quad (4)$$

where; C_{init} is initial capital expenditure, OM_t is operation and maintenance cost in year t , E_t is annual energy delivered (kWh), and r is the discount rate.

LCOW was calculated using Eq. (5):

$$\text{LCOW} = [\text{Cinit} + \Sigma((\text{OMt} + \text{Fuelt})/(1 + r)^t)] / [\Sigma(\text{Vwater,t}/(1 + r)^t)] \quad (5)$$

where; Fuelt is annual fuel cost in year t, and Vwater,t is the total volume of irrigation water pumped in year t.

RESULTS AND DISCUSSION

Hydro-photovoltaic response to variable solar irradiance

The pumping system responded positively to increasing solar irradiance. At 350 W/m², the threshold condition produced 345 ± 12 W of DC power and 1.12 ± 0.08 L/s at a dynamic head of 9.2 ± 0.4 m. At 1,020 W/m², the system produced 1,120 ± 32 W, a dynamic head of 16.2 ± 0.9 m, a discharge of 5.20 ± 0.24 L/s and hydraulic power of 826.4 W.

Table 1: Hydro-photovoltaic Response under Variable Solar Irradiance in Shani

Solar Irradiance (W/m ²)	DC Power (W)	Electrical Power (W)	Dynamic Head (m)	Discharge Rate (L/s)	Hydraulic Power (W)
350 (Threshold)	345 ± 12		9.2 ± 0.4	1.12 ± 0.08	101.0
500	520 ± 18		10.5 ± 0.5	2.25 ± 0.12	231.8
650	705 ± 22		12.1 ± 0.6	3.38 ± 0.15	401.2
800	880 ± 25		13.8 ± 0.7	4.20 ± 0.18	568.6
950 (Peak)	1,060 ± 30		15.4 ± 0.8	4.95 ± 0.21	747.8
1,020 (Solar Noon)	1,120 ± 32		16.2 ± 0.9	5.20 ± 0.24	826.4

Increasing irradiance from 350 to 500 W/m² increased DC power by approximately 50.7%, discharge by 100.9% and hydraulic power by 129.5%. At solar noon, relative to the threshold, DC power, discharge and hydraulic power increased by approximately 224.6%, 364.3% and 718.2%, respectively. The findings agreed with Akinyele and Olatomiwa (2022), who found that PV pumping performance improved under higher solar radiation but was constrained by increasing total head. The practical operating threshold of approximately 350 W/m² was higher than the approximately 50 W/m² threshold reported in comparable Ghanaian evidence, indicating that the useful threshold depended on the pump, controller, hydraulic configuration and operating head.

Seasonal solar resource, array efficiency and performance ratio

Solar availability remained strong throughout February–April. Mean daily solar irradiance increased from February to March and declined slightly in April, while array efficiency and performance ratio decreased gradually. The source study associated the April decline with ambient temperatures above 40°C, which likely increased module temperature and reduced electrical conversion efficiency.

Table 2: Seasonal Solar Resource, Array Efficiency and Performance Ratio

Month	Mean Daily Solar Irradiance (kWh/m ² /day)	Array Efficiency (%)	Performance Ratio
February	6.12 ± 0.35	14.6 ± 0.5	0.74 ± 0.03
March	6.58 ± 0.42	14.1 ± 0.6	0.71 ± 0.04
April	6.22 ± 0.48	13.8 ± 0.7	0.68 ± 0.05
Mean (Dry Season)	6.31 ± 0.42	14.2 ± 0.6	0.71 ± 0.04

The mean array efficiency of 14.2% was within a realistic field range for crystalline-silicon PV systems after practical losses. The mean performance ratio of 0.71 indicated that the system retained a substantial proportion of theoretical reference yield. The decline toward April was consistent with the temperature sensitivity of PV modules. These findings agreed with Bawa *et al.* (2025) and Akinyele and Olatomiwa (2022).



Comparative Ten-year Life-cycle Cost of Solar PV and Petrol Pumping

The solar PV system required substantially higher initial investment, but recurring costs were considerably lower. The 1.2 kWp solar unit had an initial capital cost of \$1,850 compared with \$380 for the 2.6 kW petrol pump. Discounted operation and maintenance cost was \$220 for solar compared with \$650 for petrol, while fuel expenditure was zero for solar and \$3,840 for petrol over 10 years.

Table 3: Comparative 10-year Life-cycle Cost of Irrigation Pumping

Financial Parameter	1.2 kWp Solar PV Pumping Unit	2.6 kW Petrol Motor Pump
Initial Capital Cost (CAPEX)	\$1,850.00	\$380.00
10-Year O&M Cost (Discounted)	\$220.00	\$650.00
10-Year Fuel Expenditure	\$0.00	\$3,840.00
10-Year Total Life-Cycle Cost	\$2,070.00	\$4,870.00
Total Water Volume Pumped (10 Years)	86,250 m ³	63,200 m ³
LCOE	\$0.112/kWh	\$0.418/kWh
LCOW	\$0.024/m ³	\$0.077/m ³

The solar option reduced total life-cycle expenditure by \$2,800, equivalent to approximately 57.5% lower life-cycle cost. It delivered approximately 36.5% more water over 10 years. LCOE was reduced by approximately 73.2%, while LCOW was reduced by 68.8%. The reported simple payback period was 2.3 years. These findings were consistent with Xie (2021), who emphasized life-cycle rather than initial capital cost when comparing solar and diesel irrigation, and with Lorenzo *et al.* (2018), who reported substantial PV LCOE savings across the ECOWAS region.

Operational Reliability and Irrigation Conveyance Efficiency

During the peak dry season, the solar PV system recorded 96.4% operational reliability compared with 78.2% for petrol pumps. The difference was 18.2 percentage points, with solar reliability approximately 23.3% higher in relative terms. Petrol-pump interruptions were associated with spark-plug fouling, carburetor blockage and local fuel shortages. Water delivered through low-pressure drip or flexible-hose systems achieved 82.1% irrigation conveyance efficiency.

The high reliability reflected the absence of fuel requirements and lower routine maintenance demand, although the solar system was not maintenance-free. Routine PV module cleaning, electrical inspection, pump servicing and hydraulic checks remained necessary. The 82.1% conveyance efficiency indicated that a large proportion of pumped water reached the intended delivery points.

CONCLUSION AND RECOMMENDATIONS

The study demonstrated that the solar PV-powered pumping system was technically viable, economically competitive and operationally reliable for dry-season irrigation in Shani and comparable semi-arid environments. Pumping performance increased with solar irradiance, reaching maximum measured values at 1,020 W/m². The system achieved a mean daily solar resource of 6.31 ± 0.42 kWh/m²/day, mean PV array efficiency of 14.2 ± 0.6% and mean performance ratio of 0.71 ± 0.04.

Despite its higher initial investment, the solar system had a substantially lower 10-year life-cycle cost, LCOE and LCOW than the petrol pump. Its 96.4% operational reliability and 82.1% irrigation conveyance efficiency further supported its suitability for dry-season **fadama** irrigation.

Concessional financing, cooperative ownership, equipment-financing schemes and pay-as-you-go models should be encouraged to overcome the higher initial capital requirement. Solar pumping should be combined with water-efficient irrigation methods and preventive maintenance, while farmer and local-technician training should cover operation, troubleshooting, maintenance and access to spare parts.

Expansion should be accompanied by groundwater monitoring and water-management measures to avoid excessive abstraction. Future research should evaluate multi-year performance across different crops, irrigation methods, groundwater depths, system configurations and environmental conditions, including dust accumulation and high module temperatures.



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