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Performance Analysis of a Hybrid Solar Photovoltaic- Grid Water Pumping System

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ABSTRACT – This study examines the integration of grid and solar energy resources in remote water pumping systems to improve performance and reliability. The feasibility of a hybrid solar PV-grid system is investigated to assess its technical and financial performance compared to standalone solar PV or grid systems. A unique aspect of this hybrid system is the utilization of a water storage tank instead of energy storage for solar PV conversion. The system comprises a PV array, inverter, AC motor, submersible pump, storage tank, grid supply, and control systems. The paper presents a cost-effectiveness analysis using Net Present Value (NPV), Levelized Cost of Energy (LCOE), and Internal Rate of Return (IRR) to economically evaluate the power supply for pumping systems in community areas. The study focuses on two energy supply systems: solar photovoltaic systems and the grid network. A case study is conducted in the western region of Uganda, where the pumping systems are designed to provide water for residential, commercial, and small industrial usage. To evaluate the proposed solar PV system, Matlab/Simulink software is utilized for modeling, and simulations are performed to assess the system's performance and outcomes. Overall, this research aims to explore the benefits and drawbacks of integrating grid and solar resources in water pumping systems, with a particular emphasis on the economic viability and technical feasibility of a hybrid solar PV-grid system.

Nomenclature and units

PV	Photovoltaic
Voc	Open circuit Voltage
1sc	Short circuit Current
P&O	Perturb and Observe

1.0 Introduction

It is widely acknowledged that there has been some improvement in the access to improved drinking water sources and sanitation services in the world as the world begins to implement the seventeen SDGs of the 2015 agenda. For Uganda's social, economic, and sustainable development, water is a crucial resource. According to this viewpoint, the availability of water is crucial to the socioeconomic health of the nation. Uganda's residential, commercial, institutional, governmental, and industrial sectors all rely heavily on a steady supply of water. The amount of water that will be consumed by all consumer groups, including residential, institutional/government, commercial, and industrial, assuming that no limiting factors, such as a lack of resources, a lack of pressure, a perception that the water is of poor quality, or inaccurate data, exist. (MWE Design Guidelines, June 2013).

It is crucial to assess the water demand, including the present and reasonable future daily water demand, while developing a new water delivery system. The intended source is intended to be able to supply water to the area for years to come, even though the existing system will only see the current demand. When assessing the system's future demand, the MWE Design Guidelines suggest conducting a life cycle analysis that lasts 25 years. The Uganda MWE Water Supply Design Manual from June 2014 should be followed in the design of solar PV-grid pumping systems.

No matter the power source, there will always be a need for water. There are, however, several additional factors that are unique to PV pumping systems. Understanding the link between pump working hours, available water storage, and system demand is particularly important because solar pumping systems can only produce water while the sun is powering the system. The required water flow in liters per second for the constrained solar power pumping hours of that season will need to be estimated after all needs have been considered and a total has been calculated.

However, by adding a backup power source to the solar PV, significant progress has been achieved toward a sustainable and dependable water supply that can satisfy demand. An evaluation is done to evaluate the dependability, load-sharing, and technical, as well as economic, viability of these hybrid solar PV systems.

According to Raghav *et al* (2016).'s study on a 1.5 Kw solar water pumping system, the system has a reliable life of 15-20 years. Narale et al. developed and put into use a PV pumping system to water a horticultural crop (2011). The grid supply and solar PV pump's total cost and life cycle cost were compared.

1.1 Solar PV Hybrid Pumping Systems.

Global weather patterns have been greatly altered and fuel prices have increased as a result of unprecedented climatic changes, the release of harmful chemicals into the atmosphere, and the rapid urbanization of the planet.

A country like Uganda has been highly impacted by all of these reasons because it mostly deals with agriculture, whose primary resource is water, yet the seasonal rains can't be expected owing to changes in the weather patterns around the world. Water scarcity of any kind is a severe concern in Uganda because agriculture, which still depends on seasonal rainfall, makes about 70% of the country's economy (World Bank report, June 2022).

To meet the water demand demands of communities in a nation like Uganda, which receives 5 kWh/m2/day of global annual insolation, solar energy-powered pumps have been made available as an alternative. Solar PV hybrid pumping systems are often those that have one or more backup power sources, such as grid electricity, a diesel or gasoline generator, and the wind, in addition to the solar source. These backup power sources provide the system operator with redundancy and flexibility, enabling the removal of solar equipment without reducing water output or extending water production into the night or during overcast conditions. There are typically two ways to use these supplemental power sources. They are most frequently used to supply standby power. Consider the grid power source, which is occasionally used when it's foggy or otherwise unfavorable outside. As an alternative, the power supply can be instantly mixed between solar and any available backup power sources. By eliminating changes in water production that typically occur with solar PV water pumping operations, this enables solar pumps to operate at full power. Any additional power source must match the pump motor's output voltage, phase, and frequency in order to be integrated into a hybrid pumping system. Typically, an AC generator powers solar pumps with DC motors through electronics in the motor or pump controller. A hybrid pumping system can receive reliable extra power from the electrical grid. Figure 1 shows how a solar PV grid can be incorporated to provide a backup power source, or grid, to enable sustainable pumping.

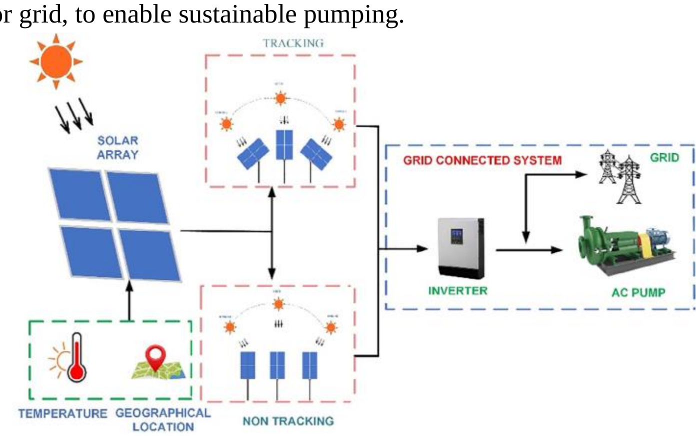

Figure 1: Solar PV water pumping system.

Estimation of water requirement for the community. Water consumption is the amount of water that is directly used by the customer, and it must be determined before National Water and Sewerage Corporation (NWSC) can determine the project's water demand. This can be done either individually or as an institution. The initial division of water usage is into several client and consumption groups, including public standpipes, residential, institutional/government, commercial, and industrial. The determination, classification, and comprehensive tariff structure of the water requirement by NWSC-Uganda are shown in Table 1.

The current water project consumption groups and their water needs must be identified in order to establish a project's water demand. The steps taken to determine the project's water consumption are described in the stages below.

Determine how the general populace uses water. In order to provide water to the community at a relatively lower cost, public water stand pipes are situated close to small towns and villages.

Determine the amount of water used at home. Domestic water use includes water used for activities such as bathing, cooking, cleaning, drinking, doing laundry, washing dishes, gardening, washing cars, and other less frequent or water-intensive activities. Depending on service levels, individual water use in rural, peri-urban, and metropolitan settings frequently varies greatly.

Establish the water use of the government and institutions. When developing and planning a water project, institutional water requirements for existing and future institutions in the project area must be calculated using data from a community survey on institutional water requirements. Schools, hospitals, government offices, the military, the police, missions, churches and mosques, prisons, and other public and private organizations are examples.

Determine your industrial water usage. Depending on the type and size of the industry, this need varies greatly. if the water supply system that is currently in place or that is planned cannot satisfy the demand. The demand must be determined at that point, and it may be essential to look into a different local water supply.

Determine your commercial water usage. Hotels, restaurants, stores, arcades, bars, car washes, tiny workshops, and service stations are all places where this consumption takes place.

Table 1 shows how NWSC-Uganda determined, categorized, and the specific tariff structure for the water requirement.

Table 1: Ugandan tariff categorization per cubic meter in Ugx

S/n	Categorization	Charges per cubic meter of water,m^3 in Uganda shillings (Ugx)
1	Public standpipe	1060
2	Residential	3727
3	Institutional/Government	3771
4	Commercial <1500m^3 per month	4473
5	Commercial >1500m^3 per month	3575
6	Industrial <1000m^3 per month	4473
7	Industrial >1000m^3 per month	2500

1US$=Ugx 3634

1.2 Related work.

Solar PV hybrid pumping systems are generally those that are equipped with one or more supplemental power sources i.e. wind, generator (diesel or petrol), grid power in addition to solar source. These supplementary sources of power offer the system operator with redundancy and flexibility thereby allowing solar equipment to be taken offline without sacrificing water production or extending water production into night-time hours or times of cloudy weather.

These Supplementary power sources are generally used in one of two ways. Most often, they serve to provide standby power.

For instance, the grid power source that is used occasionally during cloudy or other inclement weather. Alternatively, power supply can be instantaneously blended between solar and whatever supplemental power sources are available. This enables solar pumps to run at full power, removing variations in water production that normally occur with solar PV water pumping operations. For any supplemental power source to be incorporated into a hybrid pumping system, the output voltage, phase, and frequency should match those of the pump motor. Solar pumps with DC motors are usually powered by an AC generator via electronics within the motor or pump controller. The electrical grid can provide a robust source of supplemental power to a hybrid pumping system.

Numerous research on solar PV systems conducted by Qoaider.L et al. in 2009 and Rahman.S *et al.* in 2015 demonstrate that solar PV water pumping systems work well and are financially sustainable as a dependable and affordable method for irrigation. The use of solar PV technology has been demonstrated in research studies to be a technically and economically viable solution for supplying water for irrigation of regions of southern Egypt. In addition, the cost of electricity produced from solar PV is moderately less expensive per kilowatt-hour than using a diesel generator.

Review discussions on modeling, size, and system design of a stand-alone solar PV and grid system were presented by Rawat. R et al. in 2016. According to Perasamy P. *et al.* (2015), several MPPT control strategies and parameters have been addressed as having an impact on the performance of solar PV water pumping systems.

Additionally, Poompavai T *et al.* 2019 developed the control techniques of solar PV and grid as a hybrid system as one of the methods for energy management in renewable energy employed in water pumping systems. Furthermore, additional research on the water-pumping system using solar PV, thermal, wind, biomass, and hybrid technologies as energy supply sources was carried out by Gopal C *et al* in 2013.

Regardless of the fact that these existing study reviews consolidate the works that are related to solar PV and other forms of renewable energy systems like wind, tidal hydropower used for water pumping. There is a gap in an overall and complete analysis of the various subsystems and components related to solar PV and grid system in a single article that is yet to be discussed.

2.0 Materials and Methods

Analyzing the water demand.

The following functions from the geometric growth model are used to determine the design population:

$$P_n = P_n\left((1 + {}^{r}/_{100})^{n}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

In this scenario, Pn represents the projected population after n years, Po represents the current population, and r represents the projected yearly population growth rate (%).

For several years, Uganda's predicted population growth has remained steady at 3.0% per year, or r = 3.0% per year. (Reference: World Population Review 2022, available at http://worldpopulationreview.com).

According to worldometer's analysis of the most recent United Nations data, Uganda's population as of September 2021 was 45 million (source: https://www.worldometer.info).

The average daily water requirement, also known as per capita water consumption, and the design population were utilized to calculate the water demand.

$$Q = CP \times DP \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Equation 2 is used to compute the daily water demand.

Where:

Q Stands for daily water demand (m^3/day),

CP - Per capita daily consumption, and DP - design population.

2.1 The planned water pumping system is described.

The suggested solution is shown in Figure 2, which is a hybrid water pumping system made up of solar PV panels and a grid source supply. In this study, a solar PV array with a 34-kW rating will be used to provide a 7.5 kW (10 HP) submersible pump.

This is an effective method of controlling the motor to get the appropriate flow rate. Solar power is used during the day while utility power is conserved, which reduces the cost of electricity. In order to run a motor that is partially powered by solar panels and uses the remainder of the utility's electricity, an ideal method is devised and tested.

The suggested water pumping system is powered by the grid when the solar PV array's output is insufficient to run the motor. The combined utility and solar powered pumping system is the best choice for changeable insolation. As the insolation level decreases, the MPPT tracks the new maximum power point (MPP), and the utility supplies the remaining power for the required power demand. As insolation increases, the MPPT follows the new MPP, which causes a decrease in utility power. The motor will use utility power if there is no solar power.

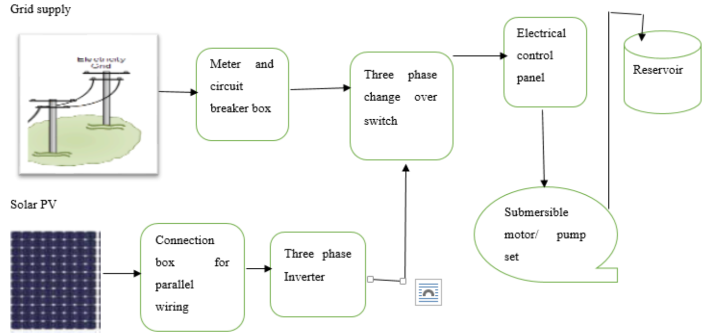

Figure 2: Hybrid PV-grid water pumping system.

2.2 Consider the input/output circuit for the solar PV system.

Figure 2 depicts the control loop diagram for a hybrid solar PV/grid water pumping system.

Take the solar PV system's input/output circuit into consideration.

The amount of incident solar energy that enters the system, Pi (in Watts), comes from the PV array.

$$P_i = I_s \times A_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

The solar PV array provides the D.C. output power, Po.

$$P_O = V \times I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Figure 3: Solar PV array for Kashaka –Bubaare water scheme.

The submersible pumps hydraulic power output, P_h is comparable to the total hydraulic power in the delivery and discharge lines at a defined head from the suction point, or it is the amount of power necessary to lift a specified volume of water over a given head, H (m).

$$P_h = \rho \times g \times Q \times H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

When converting sunlight into energy, a solar PV array's "array efficiency" E_a is used as a gauge.

$$E_a = \frac{P_o}{P_i} \ldots\ldots 6$$

The term "subsystem efficiency" refers to the effectiveness of all system components (including the inverter, pump, and motor set) E_s

$$E_s = \frac{P_h}{P_o} \ldots\ldots 7$$

The overall efficiency (E_o), measures how well a solar PV system as a whole converts solar energy into water that is delivered at a specific head.

$$E_o = \frac{P_h}{P_i} \ldots\ldots 8$$

$$P_h = P_i = E_o \ldots\ldots 9$$

$$E_o = E_a \times E_s \ldots\ldots 10$$

This equation is used to compute the overall efficiency of the array (E_a) and the subsystem (E_s).

2.3 Grid supply assessment

Energy coming from the solar PV system and the UETCL power grid, which is made up of a 50 KVA, 11,000 V/433 V, 50 Hz, three phase transformer and a 0.5Km extension of the 11KV overhead power line with three line conductors.

Figure 4: solar PV-grid system under study.

2.4 Pump modeling and the equation for pump power requirements.

According to Raghuwanshi and Khare (2018) and Mermoud (2006), system head is produced by level changes in a system, and total pump head is the sum of numerous contributing factors, including static head, dynamic head, friction losses, and head owing to outlets.

The following equation can be used to calculate the Total Head, H_{Total} in the system.

$$H_{Total} = H_{Outlet} + H_s + H_D + H_F \ldots\ldots 11$$

The outlet pipe's height above the ground is determined by this as H_{Outlet}, the static head, abbreviated as H_s is what happens when there is no pumping, and the water level is at its depth. The total friction losses plus the vertical distance from the water's surface to the water supply end H_s equals H_D or dynamic head H_F.

According to Hadidi B. et al., the solar PV-grid pump's design is dependent on the water flow (m^3/hour) and it pumps total head (2016).

After determining the entire head, water flow demand may be used to choose the pump from the manufacturer's provided graphs, and from the selected pump, it is simple to determine how much power the pump requires (Davis & Shirtliff, 2019). In accordance with Moran's 2016 tests, the amount of energy can be calculated using pump head and flow.

The subsequent was taken into consideration for the centrifugal submersible borehole pump's power supply operation. The pump's power requirements are listed as,

$$P_{in} = \left(\frac{\rho \times H \times g \times Q}{e1 \times e2}\right) \ldots\ldots 12$$

Due to that,

Power input required by P_{in} (watts)

Density of water, ρ (kg/m3)

-Pump head, H (m)

Gravity constant, g (m/s^2)

Q - Pump flow rate (m^3/hr)

$e1$ - Pump effectiveness Extrapolated from particular pump information.

Efficiency of the pump motor is $e2$ derived from a few pump details.

g = 9:81 m/s^2, H = 120 m, Q = 9 m^3/hr., when ρ = 1000 kg/m3.

$e1$ and $e2$ =70.1%.

2.5 Economic analysis of the hybrid solar PV-grid water pumping system.

The Present Value of Cost (PVC) for the solar PV system and grid system is calculated using the equation 2.12 in the system's economic analysis.

$$NPV = \sum_{n=0}^{N} \left(\frac{Cn}{(1+r)^n}\right) \ldots\ldots 13$$

Where:
NPV - Present Value Cost
Cn - Initial costs for the grid system and solar PV systems, which include transportation, installation, and cable connections.
Annual cost = Cn
The O&M cost is considered to be Cn
The discount rate, r is considered to be 10% and N is the number of operational years.
Costs for operations and upkeep (O&M) are estimated to be 2% of the initial investment.
Economic assessment using internal rate of return (IRR)

$$\mathrm{NPV} = \frac{\mathrm{Cn}}{(1+\mathrm{IRR})^{\mathrm{N}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 14$$

(Improvement and Program. 2012)

The AEC or Annual Energy Cost, is computed as follows:

$$\mathrm{AEC} = \mathrm{PVC}\left(\frac{r(1+r)^{N}}{(1+r)^{N}-1}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 15$$

Where KWH stands for yearly energy, which may be calculated using the following equation:

$$\mathrm{KWH} = \mathrm{P} \times \mathrm{n_o} \times 365 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 16$$

$$\mathrm{LCOE} = \frac{\text{Sum of cost over lifetime}}{\text{Sum of electricity generated over the life time}} \ldots\ldots\ldots\ldots 17$$

Where $\mathrm{n_o} \times$ represents the daily operational hours.
365- Number days in a year.
The load, denoted by, P is 7500W when each system is in use for six hours each day.
The levelized cost of energy suggests LCOE

$$\mathrm{LCOE} = \$/\mathrm{KWH} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 18$$

$$\text{Pump and motor utilisation combined: } 7500 \times 6 = 45000\mathrm{Wh/day}$$

Panel generation factor (PGF) for Uganda is 3.4. PGF is a factor that is taken into account when determining the size of the solar PV cells when determining the total watt peak rating.

$$\text{Energy lost in the system} = 1.3$$

$$\text{Total energy required for PV panel is } 45000 \times 1.3 = 58500\mathrm{Wh/day}$$

The PV panel's size

$$\text{Total } W_p \text{ of PV panel capacity needed} = \frac{\text{Total PV panels energy needed}}{\text{Panel generation factor for Uganda}}$$

$$\text{Total } W_p \text{ of PV panel capacity needed} = \frac{58500}{3.4} = 17206$$

$$\text{Number of PV panel needed} = \frac{\text{Total } W_p \text{ of PV panel capacity needed}}{\text{Rating of the PV panel}}$$

$$\text{Number of PV panels needed, } \frac{17206}{350} = 49.16$$

Needed PV module count: 17206/350 = 49.16 modules
Actual module count is 50.
Consequently, the system needs at least 50, 350Wp PV modules.

2.6 Size of the inverter.

A boost converter's DC-controlled voltage is transformed into regulated AC voltage by the inverter, which has three terminals and two switches on each terminal. In order to ensure safety, the inverter should be sized at 25–30% larger.

$$\text{Total load} = 7500\mathrm{W}$$

$$\frac{25}{100} \times 7500 = 1875\mathrm{W}$$

$$\text{Total invertersize} = 7500 + 1875 = 9375\mathrm{W}$$

The size of the inverter should be at least 10,000W (10KVA).

3.0 Results

3.1 Solar photovoltaic system simulation.

The PV system was simulated by modeling its components and conducting simulations. Input characteristics, such as sun insolation of 1000 W/m² and an operating temperature of 25°C, were considered. The current-voltage relationship at this radiation intensity and ambient temperature was analyzed in the design operating mode. The simulation investigation employed the P&O algorithm for maximum power point tracking. The components replicated in the PV system include the DC/DC boost converter, boost controller, LC filter, and inverter.

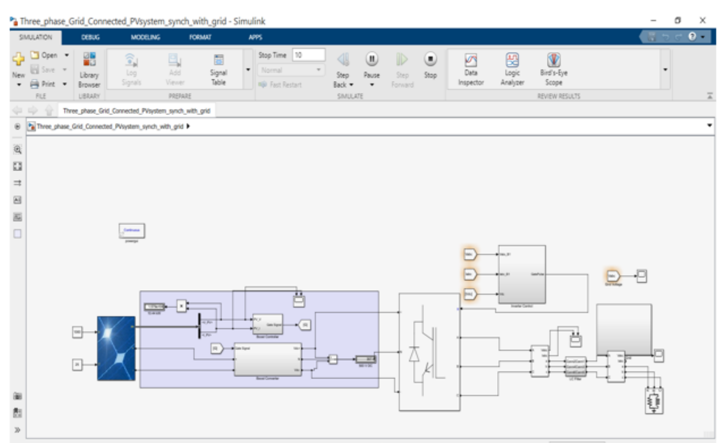

Figure 5: MATLAB/Simulink System for a solar PV simulation.

The financial evaluation of the PV-grid water pumping systems was conducted as presented in Table 2. The cost-benefit analysis takes into account both the grid power system and solar PV.

Table 2 Cost for the water pumping system using solar energy.

s/n	Item	Quantity	Price($)	Amount ($)
1	Sun Harness 350Wp solar panel	50modules	122	6100
2	Lorentz MID series dual MPPT solar Inverter	01 No.	3100	3100
3	Lorentz charge controller MPPT 100-625	01No.	669.19	669.19
4	Pump/motor set, pipes, civil works ,transportation ,installation and cable connection			8649.81
			Total	18,519

Table 3: Grid system costs.

s/n	Item	Amount ($)
1	50KVA, 3 phase power transformer, 0.5km main line extension, switch control, wooden poles and installation works.	13,375.72
2	Pump/motor set, pipes, civil works ,transportation ,installation and cable connection	8649.81
	Total	22,025.53

4.0 Discussions

The simulation's findings for the input solar irradiation of 1000 W/m^2 from the PV.

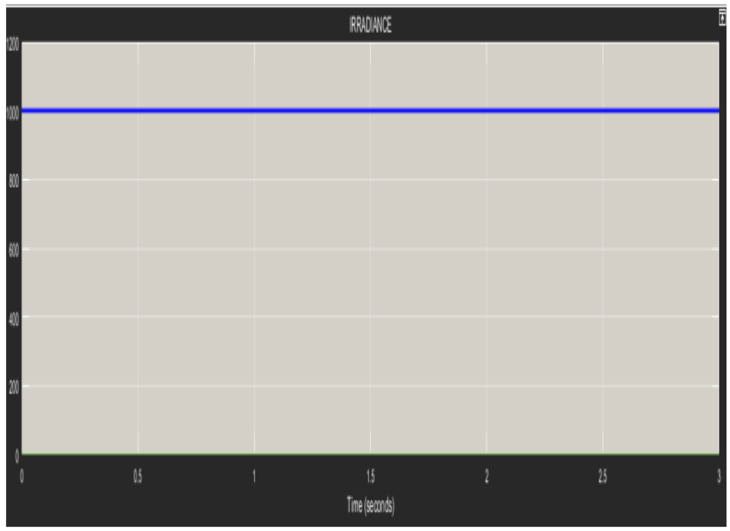

Figure 6: Solar energy input to the PV.

The solar PV panels in the simulated system have an operating temperature of 25^0 c.

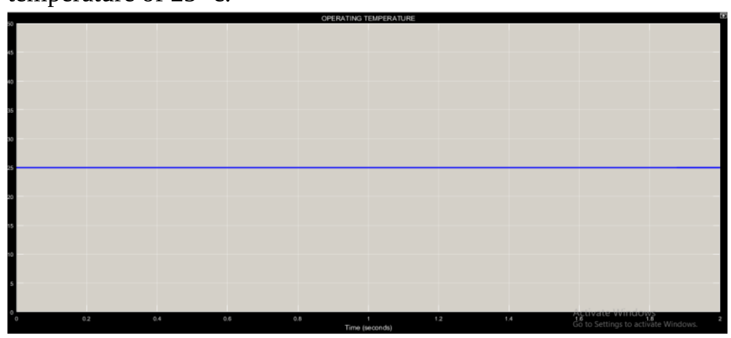

Figure 7: Operating temperature of solar PV panels.

The DC voltage that is produced by the solar PV panels.

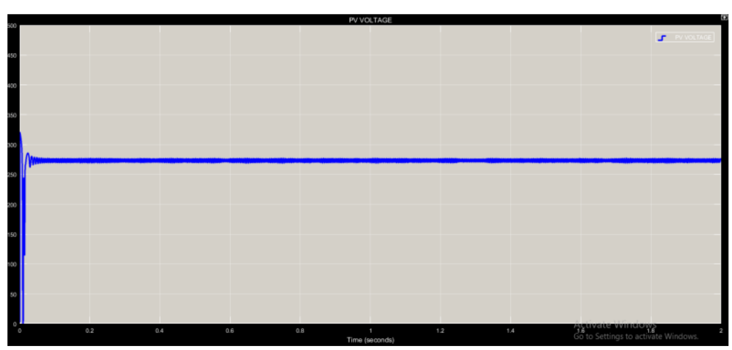

Figure 8: DC voltage that the solar PV panels create.

Solar PV panels' DC produced current.

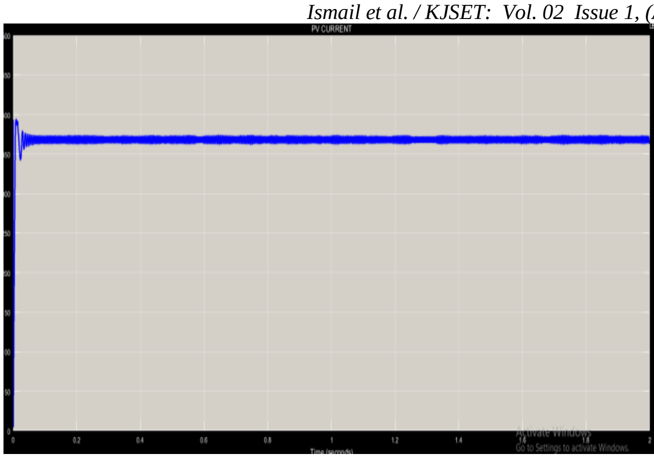

Figure 9: DC Output Current from the solar panels.

Illustration of three phase output voltage from the inverter

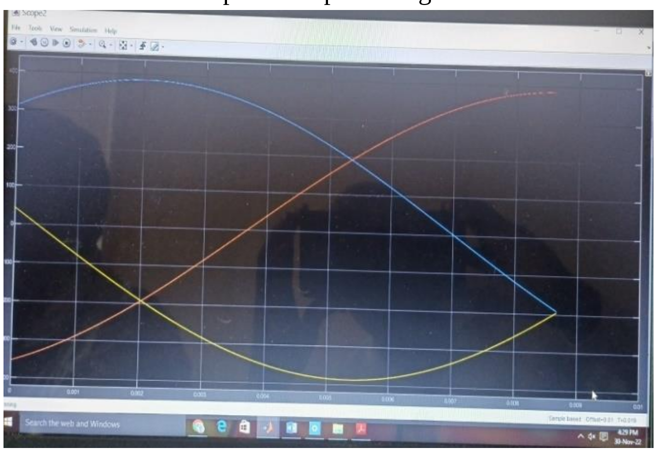

Figure 10: Output voltage being generated from the three-phase inverter.

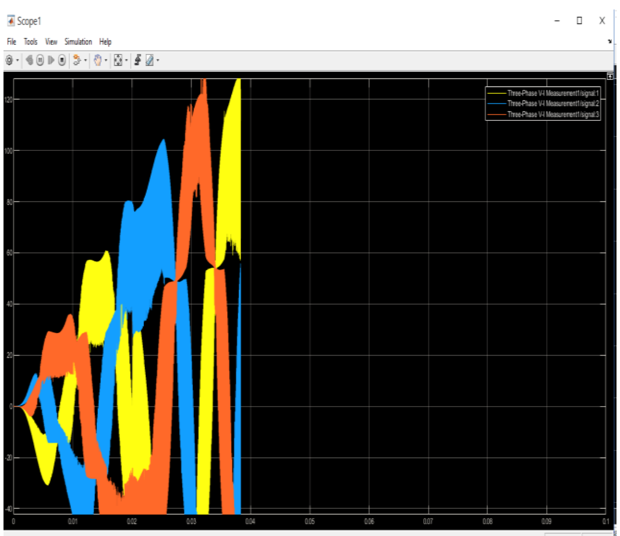

Figure11: Sinusoidal Correlation of the output AC voltage from the inverter as it forms peaks during simulation.

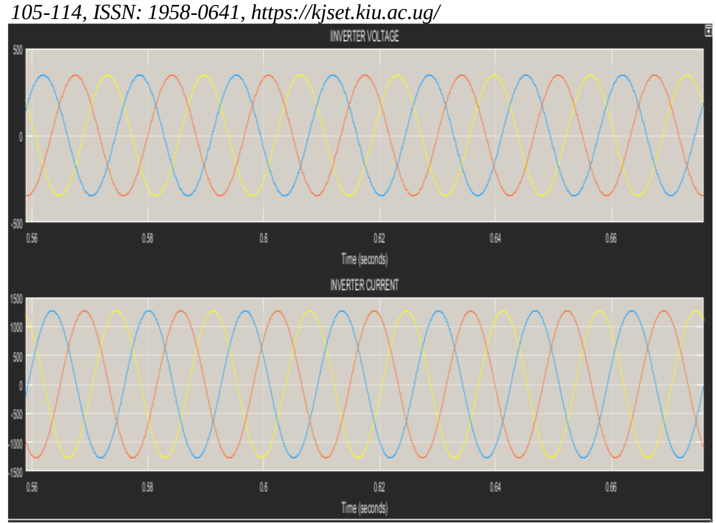

Figure 12: AC Output from the inverter and grid

4.1 Outcomes of the simulation.

The PV generator's current-voltage and power-voltage parameters, under standard test conditions (G = 1000 W/m2, t = 25°C), align with the following values. The short-circuit current is 9.60 A, while the open-circuit voltage at the generator's terminals is 46.9 V. Furthermore, the maximum power available is 52.5 kW, and both the inverter's output and the synchronous grid output are prominently depicted. Figure 12 provides a visual representation of the AC output voltage from both the inverter and the grid.

4.2 Economic Analysis.

In Table 4, the estimated cost of an electrical connection for water pumping from the distribution network is typically around US$2,202,553. This cost encompasses various components such as power transformer, labor, cables, connection box, and administrative work. The calculation of this cost was based on data provided by the distribution company. If overhead transmission lines are utilized, the approximate cost per kilometer for connecting the public distribution

Table 4: Economic Analysis of PV, Grid and PV-Grid

indicator	Initial cost ($)	O&M ($)	NPV ($)	LCOE $/Kwh	AEC ($)
PV	18,519	370.38	34.20	$1.13x10^{-3}$	3.762
Grid	22,025.53	440.51	40.67	$1.34x10^{-3}$	4.474
PV-grid	31,894.72	637.89	58.90	$9.71x10^{-4}$	6.479

network to the pumping system is determined to be US$1,000.

The utilization of underground cables would result in an increased cost. Consequently, the expense associated with implementing a PV system is lower compared to the cost of expanding the grid network, even when the grid is located merely 1 km away from the water pumping station. The analysis clearly indicates that a hybrid solar

PV-grid system was chosen due to its superior net present value (NPV) and its lower overall cost.

Table 4 presents the computed results for a lifetime of 25 years, displaying the net present value (NPV) and levelized cost of energy (LCOE). The PV-grid system has an initial cost of US$31,895, an NPV of 58.90, and an LCOE of 9.71x10-4$/KWH. Based on the results, the highest NPV signifies the feasibility of implementing the PV-grid project. Furthermore, it offers the lowest cost of energy compared to the PV-only or grid-alone options. The computed internal rate of return (IRR) for PV, grid, and PV-grid systems is 10%. This implies that all these energy system projects, whether implemented individually or in combination, are worthwhile since the IRR exceeds the assumed discount rate of 10%.

5.0 Conclusions

The research on modeling and simulating solar water pumping systems has provided a significant and valuable contribution. The numerical simulations were carried out using the Simulink simulation environment in the MATLAB interface. The primary objective was to address the issue of water storage and consumption management in rural and urban communities, with a specific focus on the Kashaka-Bubaare community.

Numerical modeling enables the analysis of multiple facets within the pumping system, encompassing individual modules and the system as a whole. Through numerical modeling, essential characteristics such as the relationships between current-voltage, power-voltage, PV output voltage-time, and inverter output voltage-time can be examined.

Based on the economic analysis comparing the suggested PV system with traditional grid-connected pumping systems, it has been concluded that a solar PV-grid pumping system is highly suitable for Uganda's environment. This determination emphasizes the system's viability and appropriateness, presenting it as a favorable alternative to conventional grid-connected systems.

The developed system presents notable benefits by efficiently utilizing the maximum power from the Solar PV array, thus reducing dependence on the utility grid. This offers a valuable opportunity to achieve substantial reductions in electricity costs. The research findings should inspire Uganda's National Water and Sewerage Corporation (NWSC) to embrace widespread implementation of PV pumping systems. By doing so, they can ensure affordable energy costs and a reliable water supply for all communities.

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Conflict of interest statement

The authors declare no conflict of interest.

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