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EDITED BY
Yanjun Shen,
University of Chinese Academy of Sciences, China

REVIEWED BY
Wahri Sunanda,
Bangka Belitung University, Indonesia
Mukesh Kumar,
University of Delhi, India

*CORRESPONDENCE
Vincent Anayochukwu Ani
✉ anayochukwu.vincent@gmail.com

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Design of a solar water pumping system for efficient irrigation systems for crop production

Vincent Anayochukwu Ani*

Energy Commission of Nigeria (ECN), Abuja, Nigeria

Agriculture is the lifeblood of human civilization, providing sustenance and livelihoods to billions worldwide. Solar power solutions are emerging in agriculture to make the industry more sustainable in the future. In Karshi village, Abuja, Nigeria, a large percentage of the population earns their living from agriculture and many small-scale farmers rely on it for their only source of income. Most farmers in this community practice crop rotation, and a key challenge they face is ensuring energy access for pumping solutions. Therefore, there is a need for a solar-powered water pumping system to be designed for irrigation systems on farms in Karshi-Abuja. The method for this study is research through case studies at different farm sites in the communities of Abuja and surrounding areas; the results indicate that the daily water demand for crop irrigation in Karshi was 10,000 litres per day for a field size of one hectare. A pump is required to supply water from a well to an elevated water storage tank. A pump that could supply a flow rate of 2.4 m^3/hour at a Total Dynamic Head (TDH) of 14.2 meters was chosen. Upon analyzing the pump curves, it was observed that the pump motor needs approximately 258 W of power to reach the desired performance. After reviewing various solar panel options on the market, a solar panel with the appropriate configuration (peak power of 110 W, operating voltage of 18.8 V, and operating current of 5.9 A) was chosen. An array of three 110-watt solar panels wired in parallel was used to produce a current of 17.7 A with a total output power of 330 W, which should suffice to power the pump.

KEYWORDS

solar power, irrigation, pump, solar panel, water storage tank, Karshi-Abuja, Nigeria

1 Introduction

Crop irrigation is vital throughout the world in order to provide the world's ever-growing population with enough food (USGS, 2018). Irrigation is the controlled application of water for agricultural purposes to provide water needs that are not met by rainfall. In Nigeria, a large percentage of land is devoted to rain-fed production, while a small percentage of land is irrigated (FAO, 2020). Nigeria's rain-fed agricultural systems will need better irrigation systems to improve crop yields since most farmers resort to manual means of crop irrigation when there is no rain. More frequent droughts and water shortages represent a big risk to livelihoods and food security, especially for the most vulnerable populations in rural areas (AfCFTA Workshop, 2024). In the Karshi, Abuja, community, a significant percentage of the population earns their living from agriculture. Many small-scale farmers work all day to provide food for their own families and selling produce when there is surplus. These farmers struggle to obtain enough water to irrigate the crops, thus a more sustainable solution for small-scale farmers' irrigation systems will focus on using reliable, clean-energy solutions. For this purpose, this work developed practical design and procurement considerations to employ photovoltaic (PV) modules to power an irrigation pump lifting water from a well to an elevated storage tank.

For irrigation, motor-driven pumps are used to raise water from a lower to a higher level, from which it flow by gravity through channels to the fields. Most water pumping for irrigation purposes is powered with fossil fuels (diesel or petrol). Petrol-fueled pumps are a very common option for smallholder agriculture and are characterised by low initial costs, low weight, a comparatively short lifespan, high fuel consumption, and high maintenance requirements. The diesel-fueled pumps are very popular among farmers because they are easy to work with, deliver water to plants faster, due to the ease of work for farmers and the faster delivery of water to plants, and last much longer than petrol-fueled pumps. The disadvantages of fossil fuels are well known. While diesel motors have an initial low cost but fueling, repair, and maintenance causes operation costs to increase over time. In addition, they can lead to pollution of soils and groundwater. A solar-powered pump is different from conventional pumps because it does not need fuel or electricity from the grid or a generator to operate. A solar-powered pump can be a cost-effective, environmentally-friendly, and low-maintenance way to meet water needs for agricultural irrigation and are particularly suitable for remote areas with no or unreliable power grid.

A solar water pumping system (SWPS) uses PV panels to drive a pump that sucks up water from a particular source and discharges the water either to an over-head tank or piping within a long distance where water is needed (Omoraka et al., 2023; Odesola and Bright, 2019). Solar-powered irrigation systems (SPIS) have been practiced since the 1970s (Gualteros and Rousse, 2021; Bahadori, 1978; Dannies, 1959; Pytilinski, 1978; Wenham, 2007; Hartung and Pluschke, 2018; IRENA and FAO, 2021) and has been considered a technology change in the irrigation and agriculture sectors. In fact, it is only the energy system that changes and not a mechanical system, of the irrigation system and therefore the classification is driven by the typology of energy systems (Shirsath et al., 2020). With recent improvements in efficiency and innovations in delivery and financing models, its attractiveness has grown, as has its deployment (Hartung and Pluschke, 2018). Solar pumps have several advantages that make them a good choice for modern farming They do not contribute to CO_2 emissions, are simpler to design, and have fewer moving parts; thus reducing malfunctions and repair costs. There are also challenges and considerations that farmers need to know about when implementing a SPIS. One of the primary challenges is the high initial investment cost for equipment and installation for smallholder farmers with limited financial resources. However, it is important to consider the long-term savings and benefits these systems offer, as they often outweigh the initial investment. Besides the high cost of solar irrigation systems, other challenges are access to finance, especially for small-scale farmers, as well as the availability of good products and services and that can operate during daytime.

Many successful SPIS have been implemented in different regions and for variety of farming practices. For example, they have been adopted by large-scale commercial farms, such as the Bowery Farming facility in New Jersey, United States. Bowery Farms has been able to grow a variety of crops year-round using solar panels and advanced hydroponic technology. Additionally, the farm's carbon footprint is reduced, making it a sustainable and environmentally friendly operation. Another successful case study is the Solar Pump Irrigators' Cooperative Enterprise (SPICE) in India. SPICE is a community-based organization that helps smallholder farmers use solar irrigation systems. SPICE has helped farmers switch from diesel-powered pumps to solar-powered systems by offering financing options and technical support. Farmers have been reporting increased crop yields, reduced operational costs, and better access to water. After the introduction of the SPIS, farmers in Bihar, India, were able to switch from deficit to full irrigation, which improved plant health, increased crop yields, and extra income from selling the excess produce (GIZ, 2013). In the Sudano-Sahel area of Northern Benin, SPIS was installed in vegetable gardens formerly watered with cans and hauled water. This allowed the women farmers to become net producers of vegetables, make money from market sales, and increase their household nutrition intake and food security (Burney et al., 2009). In Maharashtra, India, replacing diesel pumps with SPIS helped improve the on-farm economic benefits. These were in part due to micro-irrigation practices integrated with SPIS, which allowed for reduced input costs, increased productivity, and higher yields (Honrao, 2015).

Various studies have compared the costs of using conventional and alternative energy technologies for irrigation water pumping at the site scale (Girma et al., 2015; Hossain et al., 2015; Kelley et al., 2010; Lorenzo et al., 2018). There are big differences in investment and running cost when comparing between solar-powered, fuel-powered, and electric powered systems. The solar-powered system was much more expensive than the other two systems. But it could still be justified when compared to the fuel-powered system, because of the high running and maintenance costs as well as the short life of the fuel pump. It is harder to justify the economic advantages of the solar system compared to the electric pump. However, since electricity in Nigeria is not always reliable, farmers should invest in a solar system if they can afford it (Oba, 2018).

Considering that all systems use a lot of water, the environmental impact of water collection is about the same. However, the remaining environmental impact is different (Oba, 2018). The CO_2 emissions from the SWPS are negligible. On the other hand, there is a significant amount of emission from the use of petrol. By burning 1 L of petrol, 2.3 kg of CO_2 which is released in the atmosphere (U.S. EIA, 2015). In summary, using solar water pumps is a good way to water plants without harming the environment. Solar-powered irrigation systems are good for small farmers because they save money on fuel and maintenance. They also have a good return on investment, which can last for many months or years.

The assessment of crop water needs can be done by calculating irrigation water requirements (IWR). The net IWR is the amount of water required for crop growth. It is expressed in mm / yr or in m^3 / ha per year $\left(1\,mm = 1l / m^2 = 10m^3 / ha\right)$. It depends on the cropping pattern and the climate. Each crop has its own water requirements, and multiple cropping periods have to be taken into account when calculating crop water requirements for each crop (Frenken and Faurès, 1997; Sass and Hahn, 2020). For solar irrigation, data on water needs, access to and availability of groundwater is often needed. According to Sass and Hahn (2020), the data required to design a solar-powered irrigation system are: crop data (crop type, growing season, crop rotation, and water demand); water data (availability of water); site data (longitude, latitude, water source, and pumping head); and meteorological data (insolation and temperature). Therefore, the objective of this study is to design an efficient solar-powered water pumping system that would be built for irrigation systems on farms in Karshi-Abuja.

1.1 Benefits of deploying solar energy for irrigation systems in Nigeria

Solar energy can help irrigation systems in Nigeria by solving key problems, like reliable power for irrigation and a reduced dependence on fossil fuels. Nigeria's agriculture is driven by smallholder farmers, who constitute over 80% of the total Nigerian farmer population and are based in rural Nigerian communities. A reliable power supply is a major obstacle to efficient irrigation. Solar PV systems can be used to power irrigation pumps, allowing farmers to use less water efficiently and increase crop yields.

1.2 Proposed solar water pumping system for irrigation

In the proposed SWPS for irrigation, electricity is generated by solar PV panels and used to operate pumps for the abstraction, lifting and/or distribution of irrigation water. SWPS can be used in a wide range of applications, from individual or community vegetable gardens to large irrigation schemes. This system has four main components.

- Solar panel.
- Electrical controller.
- Electric-powered pump.
- Water storage tank.

1.2.1 Solar panel

A solar panel is made up of multiple solar cells that are assembled in a series. It comes in different sizes and power ratings. In most situations, a single panel will not provide enough power for a water project (Ani, 2016). In order to increase power output, multiple panels are connected together as an array in series, parallel, or both. In series arrangement of solar panels, the voltage output will be the sum of the voltage outputs of all the individual panels, while the current will remain the same. When placed in parallel, it becomes the opposite. Thus, the wiring configuration of the solar array has a direct impact on whether the voltage or current increases (Water Mission, 2018). The required size of the solar panel array depends on factors such as solar radiation levels, pump power requirements, and irrigation schedule. A good estimate of the solar panel capacity ensures that enough energy is generated to meet the pumping system's needs (Bawa et al., 2023).

1.2.2 Electric controller

An electrical controller is important for a SWPS. The electrical controller is an important part of every solar charging system (Odesola and Bright, 2019). It controls the electrical power from the panels to the pump and provides protection in the system. The solar panels can be disconnected from the system by using a main switch in the component. When the panels are not producing enough power to meet the pump's minimum power requirement, the controller can switch off the pump. Furthermore, if the panels produce too much power, the controller can limit the power to the pump to prevent the pump from exceeding its maximum speed rate. A safety device can be added to the controller to prevent the pump from running dry under low-water conditions (Morales and Busch, 2010).

1.2.3 Electric powered pump

The pumps in a solar water pump system are usually powered by direct current (DC) electric motors, and the type of pumps used for irrigation systems mostly depends on the water requirements and type of water source (Morales and Busch, 2010). It is important to know the motor's power, voltage range and maximum current draw.

1.2.4 Water storage tank

For irrigation, a convenient way to store energy generated by solar panels is through the use of a water storage tank. As reported by Morales and Busch (2010), the goal of a solar-powered water pump system is to store water, not electricity. Therefore, the tank serves as a storage facility for water from periods of high insolation, when energy production is high, to periods where energy production is low. Preferably, the amount of stored water should be enough to satisfy the water needs for at least 3 days, depending on the location's climate (Morales and Busch, 2010). Furthermore, it is necessary to elevate the tank in order to guarantee sufficient gravity-induced pressure to distribute the water to the field. Therefore, identification of a proper elevated support structure for the tank should be part of the complete water system design, which includes the Total Dynamic Head (TDH) calculation (Water Mission, 2018).

2 Literature review

A number of papers have been written about solar PV water pumping systems, and several studies have been conducted on sizing techniques and optimization aspects of solar-powered water pumping systems. All these papers use the same method of pump sizing which mainly depends on the flow rate of water and the dynamic water head, but they use different methods of sizing the PV array which mainly depends on the efficiency of PV modules and the quality and quantity of solar irradiance available in the location of water source (Almarshoud, 2016). The reviews by Gualteros and Rousse (2021) show that the proposed methods for sizing are very similar in most of the published articles. System sizing is one of the most important steps in determining the solar-powered water pumping system's long-term performance. In other words, a mistake in sizing can lead to poorer system performance, by which the system is not capable of pumping enough water when confronted with expected consumption (Wenham, 2007).

Lunaria et al. (2021) used particle swarm optimization to determine the optimal soil depth for minimizing drip irrigation costs. They tested a solar-powered drip irrigation system, and found that it is comparable to diesel-fueled drip irrigation systems in output while using less water. They concluded that integrating renewable energy with irrigation, especially using particle swarm optimization, can reduce irrigation costs. Miran et al. (2022) designed a standalone solar drip irrigation system and analyzed its potential for energy generation and water management. The study demonstrated that standalone PV drip irrigation systems can improve farm water management and use precious water resources wisely. Grant et al. (2022) presented the solar-powered drip irrigation optimal performance model to optimize system designs. Their findings show that solar-powered drip irrigation could work in real-world conditions; and could make solar-powered drip irrigation more accessible to smallholder farmers.

Ogunnubi et al. (2020) designed a solar PV drip irrigation system to address the water shortage and quality issues at Auchi Polytechnic in Nigeria and the surrounding communities. The system was tested using maize, pepper, and tomatoes as test crops to see how uniform the water emission from the drip emitters into the field was. The result showed that the low-cost drip irrigation system developed has a high level of efficiency and uniform water emission across the entire study area. Findings indicate that the system was able to deliver water to the plant where most of the water can be used for plant growth, resulting in little water being wasted in supporting surface evaporation or weed growth. Diarra et al. (2021) designed a PV-powered drip irrigation system for vegetable crops in Bellel, Guinea. They calculated a total water requirement of 150 m^3 per day to irrigate 7 ha, with 50 m^3 allocated to each crop. The PV array consisted of 5 modules in series and 3 in parallel, totaling 15 modules. The obtained results were used to design a drip irrigation system powered by PV energy in Bellel, Guinea. Mejeed et al. (2019) designed a solar PV pressurized drip irrigation pumping system for tomato crops in the AL-Salman district of Iraq. The results show that a solar pumping system with a maximum flow rate of 64.45 m^3/h and a pump capacity of 16.79 kW is feasible. It also indicates that peak operating times for 8 months were 7.2 h/day and 5.2 h/day for the remaining 4 months. Findings show that the designed system was able to meet the water needs for tomato crops, with an annual water production of 230,000 m^3. It also shows that the efficient use of solar energy made the system suitable for sustained irrigation. Ghosh and Biswas (2017) conducted an experiment to see if a water storage structure, drip systems, and PV solar pump could be used for orchard irrigation. Findings shows that the system could help address water shortage in the western part of West Bengal, especially in the summer. Almarshoud (2016) presented a novel approach for sizing the PV array of water pumping systems. This approach uses the solar irradiance data on determining the starting value of the solar irradiance on the global solar radiation curve. A case study from Buraydah city in the middle of Saudi Arabia was selected to apply the sizing approach. The results showed that a 30 kW pump that needs to deliver 200 m^3 of water daily from a well of a 176 m depth, may be driven by a PV array of 227 modules of type (SPR-210-BLK). The case study showed how easy it is to use the proposed method while the needed solar radiation data is available. Most research uses the monthly average of daily solar insolation data to calculate the associated peak sun hours as a base for sizing the PV array. This method is not always adequate, as the determination of operation hours is difficult, as it depends on the amount of sunlight during the day. In this paper a simple and accurate approach has been proposed for sizing the PV array. This approach depends on the nominal power of motor pump system.

Cuadros et al. (2004) based their research on a method for determining the size of a solar installation that was used to power a pumping system for drip irrigation in an olive tree orchard in southwest Spain. They used three criteria: (1) Determine how much water an estate needs based on its soil-type and climate. (2) Perform a hydraulic analysis of the pumping system to determine the depth of the aquifer and the height needed to stabilize the pressure in the water distribution network. (3) Determine the peak PV power required to irrigate a 10 ha sub-plot of the estate, taking into account the overall yield of the PV-pump-irrigation system. This study was among the first in a line of research that aimed to develop a computer program to accurately and simply optimize a solar installation sizing to power an irrigation pumping system for a certain crop at a specific site.

Gualteros and Rousse (2021) looked at the scientific literature on solar-powered water pumping systems and found that Pande et al. (2003) proposed several criteria for designing a PV pumping system for crop irrigation. First, water requirements are determined for each plant, as well as the theoretical energy needed to pump water according to these requirements, taking into account pressure losses. In terms of water consumption, many variables are mentioned, such as the phases of plant growth, soil type and season. Also, the consumption pattern varies over time throughout the year. However, only the peak consumption is considered when designing the system. The selection criteria for a pump are the volume of water to be pumped, the working pressure of the system, the pressure drops and the efficiency of the pump-motor assembly. However, the process of selecting the pump is not explicit. The number of PV modules is based on the theoretical efficiency of the pump-motor unit, the nominal power of the modules and the rated power of the pump. These criteria ultimately showed key development milestones for future solar-powered water pumping systems. Therefore, the design in this paper will follow the criteria listed here by Pande et al. (2003).

3 Research methodology

Karshi is a satellite town in the Abuja Municipal Area Council (AMAC), one of six council areas of the Federal Capital Territory (FCT) (Ojo et al., 2021). The Karshi area council is located south-east of the FCT, and has a boundary with Nasarawa State (Oduwole and Eze, 2013; Felix et al., 2024). Karshi falls within Latitude $8^\circ 36' 54''$ to $9^\circ 10' 8.4''$ North of the Equator and Longitude $7^\circ 3' 7.2''$ to $7^\circ 37' 37''$ East (Longitude-Latitude-Maps, 2024; The GPS Coordinates, 2024). It is about 50 km from Abuja city centre (Mohammed et al., 2016). Karshi is still largely underdeveloped, despite its linkage to the Abuja main town (Okezie et al., 2022). However, the area is predominantly rural and mainly consists of indigenous communities from rural areas who are mostly involved in farming and related activities.

Karshi observes three weather conditions per year. This includes the rainy season, which is warm and humid, and the dry season, which is very hot and dry. In between these seasons, there is a short period of harmattan (December to January) accompanied by the north-east trade wind, with the main features of dust haze, intensified coldness, and dryness (Ajibade et al., 2021). There is also a period of dust-free weather (November and February); which is known for its high irradiance and clear weather conditions, while March marks the transition from the dust-free period of February to the rainy season. The wet season, which starts in April and ends in October, experiences its peak rainfall in June and September. Karshi experiences cooler conditions during the rainy season, even though it has high temperatures on average. Karshi weather conditions are very good for agricultural products such as tubers, root crops, grain, and vegetables. Farming activities are undertaken on a smallholder basis, with per capita land ownership averaging about 0.5 ha (Safirat et al., 2023). Notably, the farmers plant crops like yams, cassava, maize, plantains, tomatoes, onions, pumpkin, pepper, sorghum, groundnut, guinea corn, rice, beans, wheat, garden egg, melon, and watermelon.

Karshi farmers are involved in both rain-fed agriculture and irrigation farming. During the rainy season, farmers plant crops that thrive when there is water, like vegetables and groundnuts. During the dry season, farmers consider planting crops that can germinate during that period, like tomatoes, and they find it hard to water their plants to keep their produce green under the blazing sun. During this season, farmers either use manual crop irrigation or use fossil fuel-powered pumps, which results in them being overburdened financially and physically. Farmers irrigate from water wells during morning or evening, and have limited access to energy to implement pumping solutions. Therefore, there is a need for a feasibility study and design of a small-scale SWPS that could be built in this community. In order to ensure efficient system operation, a proper match between the pump and the PV module(s) was taken into consideration.

4 Design of proposed solar-powered water pumping system for irrigation

The proposed solar-powered pumping system's design is described in the following subsections.

4.1 Analysis of the system

During the dry season, demand for water is highest. The design month for the system will be August, which is the month with the lowest insolation from Table 1. Most farmers in this community practice crop rotation, and tomatoes are among the crops that generate the highest income during the dry season. Groundnuts and vegetables (non-water-intensive crops) are usually rotated with crops because these are the most commonly grown crops during the rainy season. So, these crops (tomatoes, groundnuts and vegetables) were chosen. The water needed for irrigation is based on the water requirements for the crops that are cultivated. Since pump capacity is selected based on the water demand of the drip irrigation system, factors such as crop water requirements, field size, and desired flow rates are considered to ensure adequate water supply for efficient irrigation (Bawa et al., 2023). The amount of water required for the selected crops are: groundnut: 7 m^3/day, every fourth day; vegetables: 2 m^3/day, every fourth day; tomatoes: 9 m^3/day, every third day. Consequently, the irrigation system design will focus on tomatoes, which need the most water.

The water source for this system is a well and a submersible pump with an 8 meters dynamic head was chosen for the design. The assumption is that the system's water tank should be able to hold 3 days of water needs. It is known that solar panels do not always have perfect weather conditions. In this scenario, the system will be designed to pump all the required water in 1 day. For tomatoes this means pumping 9 m^3 in 1 day and using it when needed on the third day. Thus, the system requires a 10 m^3 tank. This system will use a plastic tank measuring 2.5 m tall and 10 m^3 in volume with inflow at the top and discharge at the bottom. A DC pump that will lift 10,000 L per day is the recommended choice in this design.

4.2 Solar panel location and insolation

The location of the solar system in Karshi Abuja was chosen from the site database of National Aeronautics and Space Administration-Surface meteorology and Solar Energy (NASA-SSE), and the meteorological data was generated from the site database of the Hybrid Optimization Model for Electric Renewable (HOMER) software (Ani, 2015). Table 1 shows the monthly average of daily insolation for this study.

4.2.1 Data validation through simulation

In order to verify and validate the measured solar data from NASA-SSE, the simulated data predicted by the HOMER software program must match the measured data. Figure 1 shows that the HOMER simulated data are relatively similar to the measured NASA-SSE data.

4.3 Solar water pumping system for irrigation

The SWPS is made up of multiple solar panels or solar arrays that are mounted on a structure. PV technology converts solar energy into DC electricity which drives the motor pump. A motor will pump water from a well through a pipe to an elevated water storage tank. Figure 2 shows the system layout of the designed SWPS for irrigation.

4.3.1 Designed flow rate for the pump

In solar pumping schemes, it is helpful to set a design month which will be considered as a reference to size the system. For irrigation, to ensure enough water for any month, it is typical to base the design on the worst month of the dry season because it represents the lowest ratio of solar irradiance to required water. Once the design month is known, the required average pumping rate during a day can be estimated by dividing the water required by the peak sun hours as shown in Equation 1. For this design, the least amount of insolation was chosen, which is August (4.22), and the reason for this is to make sure that the system is not undersized in any month of the year. The formula to calculate the pump's flow rate is:

$$Q = \frac{D}{S} = \frac{10m^3 / day}{4.2h / day} \approx 2.4m^3 / h \tag{1}$$

TABLE 1 Monthly insolation in Karshi, Abuja.

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Peak Sun Hours (kWh/m^2)	NASA-SSE	5.83	6.05	6.08	5.82	5.42	4.94	4.45	4.22	4.59	5.08	5.77	5.75
	HOMER	5.80	6.06	6.16	5.86	5.39	4.98	4.51	4.23	4.61	5.07	5.79	5.74

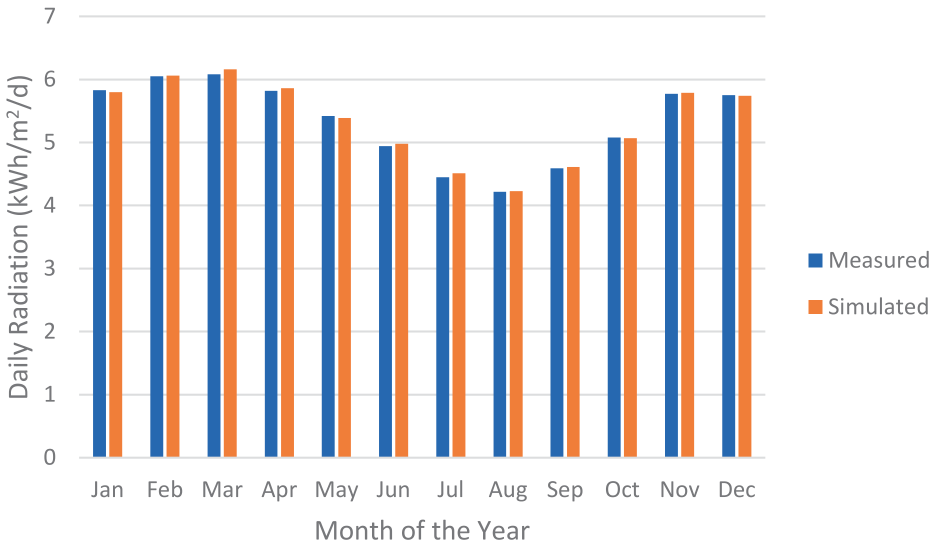

FIGURE 1
Measured versus simulated solar radiation.

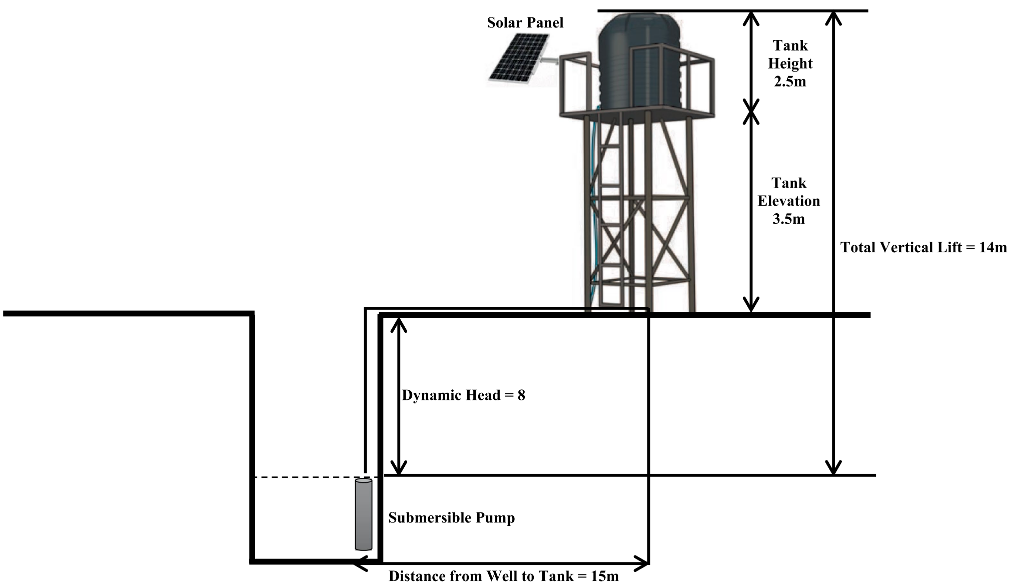

FIGURE 2
System layout of the designed SWPS for irrigation.

Where Q is the minimum required average of pump flow rate in m^3/h, D is daily water demand in m^3/day, and S is the peak sun hours in h/day.

4.3.2 Total dynamic head for the pump

The total dynamic head of a pump is calculated by combining the vertical lift (the vertical distance between the water surface to the source and the water surface in the tank), with the pressure head (the pressure at the delivery point in the tank) and friction losses (pressure losses due to friction in the pipes) (Bengtsson and Nilsson, 2015). In this design, the pressure head is zero because the tank's inlet is on top. The vertical lift can be calculated using Equation 2:

$$V = DH + TE + TH = 8m + 3.5m + 2.5m = 14m \quad (2)$$

Where V is the vertical lift in m, DH is the dynamic head in m, TE is the tank elevation, and TH is the tank height in m. To estimate friction loss, calculate the length of the pipe in, as the sum of the vertical lift and horizontal distance from the well to the tank as shown in Equation 3.

$$L = V + DT = 14m + 15m = 29m \quad (3)$$

Where L is the length of pipe in m, V is the vertical lift in m, and DT is the distance from well to tank in m.

The friction loss in plastic pipe with standard inside diameter (SIDR) table is used to calculate the extra head required for the selected pump because of pipe friction. The table takes into account flow rate, pipe size, and pipe length. Therefore, the length of the pipe from the pump to the tank inlet was also taken into consideration. From the table in Appendix A, a flow rate of 2.4 m^3/h (40 L/min) is between 38 L/min and 42 L/min, and a pipe diameter of 2″ (50.8 mm) is preferred. The friction loss of the selected pipe (50.8 mm) was calculated from a friction loss table as 0.26, which is between 0.24 (for 38 L/min) and 0.28 (for 42 L/min). Equation 4 below calculates friction loss.

$$F = \frac{FD}{100m} \times L = \frac{0.26m}{100m} \times 29m = 0.08m \quad (4)$$

Where F is the friction loss in m, FD is the friction of selected diameter in m, and L is the length of pipe in m.

This system design doubled the friction loss to make sure the system would not be undersized.

$$Friction\ loss\ doubled = 0.08 \times 2 = 0.16 \sim 0.2m$$

The friction loss is now added to the vertical lift to obtain the total dynamic head for the pump as shown in Equation 5:

$$TDH = V + P + F = 14m + 0 + 0.2m = 14.2m \quad (5)$$

Where TDH is the total dynamic head in m, V is the vertical lift in m, P is the pressure head in m, and F is the friction losses in m.

4.3.3 Pump selection

The choice of a pump type depends on factors such as water source depth, discharge requirements, and system efficiency. The pump can be chosen based on the known TDH and flow rate. For the designed flow rate and TDH, a solar submersible pump would probably be the most suitable choice for this configuration. From the window shopping at some solar water pumps and pipes shops in the city centre of Abuja, it was discovered that Lorentz products, especially Lorentz PS150 C-SJ5-8 were the most common brand for solar pumps. The best Lorentz PS150 C-SJ5-8 solar submersible pump system was chosen based on the pump's performance curve that depends on the manufacturer's specifications. From the performance curve, this pump needs 0.26 kW power for a well with 14.2 m of TDH and 2.4 m^3/h of water flow. Figure 3 shows the performance curve and operating point for this configuration. According to the performance curve, the required power for the pump is 258 W. The maximum input current of the pump is 18 A, while the required minimum voltage for the pump is 17 V, with a maximum input voltage of 50 V. This wide voltage range makes sizing easy by enabling the motor to operate at any voltage from 17 to 50 VDC (Benghanem et al., 2023). Table 2 shows the technical specifications of the PS150 C-SJ5-8 solar submersible pump system.

4.3.4 Solar panel selection and array layout

The pump peak power required is 258 W, and in order to obtain sufficient peak power from the panels, they had to be oversized by at least 25%.

The PV panels were oversize by 25% to provide sufficient power to supply the peak power of 258 W required by the pump (Equation 6).

$$RP = PP \times 1.25 = 258 \times 1.25 \approx 323W \quad (6)$$

Where RP is the required solar panel peak power in W watts, and PP is the pump peak power in W.

Many types of solar modules around the world are available, with prominent manufacturers including Canadian Solar, Trina Solar, First Solar, Jinko Solar, JA Solar, SunPower, Yingli Green Energy, Sharp Solar, Renesola, Hanwha SolarOne, EverVolt, Kyocera, and SolarWorld, among others. The industry is highly competitive and dynamic, and being the largest manufacturer does not always mean the highest quality module, as some smaller manufacturers may also offer premium products. Solar panels have several characteristics that are important for estimating their power output, and these characteristics are listed in the solar panel specifications and datasheets of the manufacturer. After investigating different panels sold in Abuja, a panel with a suitable configuration was chosen based on quality and performance specifications. The chosen solar panel's electrical performance specifications were a peak power of 110 W, operating voltage of 18.8 V, and operating current of 5.9 A. Table 3

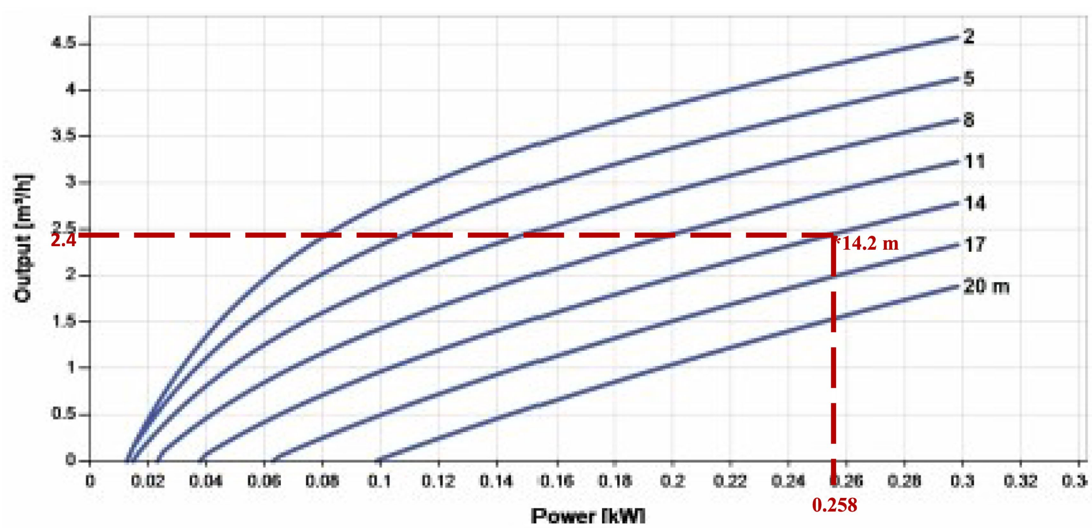

FIGURE 3
Pump performance curve for Lorentz PS150 C-SJ5-8 solar submersible system (Bernt Lorentz GmbH and Co. KG, 2024).

shows the technical specifications of SunPower (SPR-E-Flex-110) solar PV modules.

The number of solar panels is calculated from Equation 7 below:

$$P_N = \frac{RP}{P} = \frac{323W}{110W} = 3\ panels \quad (7)$$

Where P_N is the number of panels, RP is the required solar panel peak power in W, and P is the panel peak power in W.

The pump's voltage requirements has already been met by one panel. In order to ensure the pump does not exceed its maximum input voltage, three panels are connected in parallel. The panels' configuration will be:

$$Output\ voltage = 18.8\ V$$

$$Output\ current = 5.9\ A + 5.9\ A + 5.9\ A = 17.7\ A$$

$$Total\ output\ power = 18.8\ V \times 17.7\ A = 332.8\ W$$

The peak power of the solar PV system is 0.33 kW, and it consists of three panels connected in parallel. Therefore, an array that has this connection meets the pump's requirements.

TABLE 2 Technical specifications of PS150 C-SJ5-8 solar submersible pump system.

Total dynamic head (TDH)	Flow rate (FR)	Max power voltage (V_{mp})	Open circuit voltage (V_{oc})	Max power current (I_{mp})
Max. 20 m	Max. 4.0 m³/h	17 V	Max. 50 V	18A

TABLE 3 Electrical characteristics of SunPower (SPR-E-Flex-110) solar PV modules.

Nominal power (P_{nom})	Rated voltage (V_{mpp})	Rated current (I_{mpp})	Open circuit voltage (V_{oc})	Short circuit current (I_{sc})
110 W	18.8 V	5.9 A	22.8 V	6.3 A

5 Discussion

This study is based on case studies and success in similar settings where a solar-powered water pumping system has been used as a replacement and had positive outcomes. The approach in this study is to select a PV array that will size the motor pump system, and make the motor start pumping to meet water demand. As a reference to an article from Water Mission (2018), the voltage supplied by the solar array will need to exceed the minimum voltage required by the pump motor, or the pump will not start; and that the voltage from the solar array must not exceed the maximum voltage acceptable to the pump motor, or it will damage the motor. Also reported in Morales and Busch (2010), the panels should exceed the pump's minimum required voltage, but should not exceed the pump's maximum input voltage and current. In this design, the solar output voltage of 18.8 V is rated above the pump's required minimum voltage of 17 V. The output voltage (18.8 V) and output current (17.7 A) from the solar array are rated below the pump's maximum input voltage (50 V) and the pump's maximum input current (18 A). This is quite reliable and trouble-free when properly installed. Table 4 shows the specifications of the components in the designed solar-powered water pumping system; and a price for the whole system can be investigated by contacting different solar water pumping system dealers.

5.1 Comparative performance metrics with existing irrigation solution

When comparing SPIS installations to other irrigation options, the greenhouse gas (GHG) emissions (g CO2-equivalent) are an appropriate metric to measure emissions savings. GHG emission is measured in units of power produced (per kWh), water volume pumped (per m^3), equivalent hydraulic energy (i.e., the product of water flow, m^3, and pumping head, m^3), or hectare of irrigated area (per ha). Another indicator of the success of SPIS is the level of livelihood. Livelihood improvements can be captured through net income from crop production, which reflects a reduction in the cost of pump operation and maintenance, intensification and diversification towards other higher-value crops.

TABLE 4 Summary of the components in the designed solar powered water pumping system.

Components	Peak power requirement (W)	Required voltage (V)	Max input voltage (V)	Max input current (A)	Volume (m^3)	Type	Length (m)	Diameter (mm)
Submersible pump	258	17	50	18				
Solar panel	110	18.8		5.9				
Solar panels configuration—three panels in parallel wiring	332.8	18.8		17.7				
Water tank					10	Plastic		
Pipe						PVC	29	50.8
Irrigation system						Drip		

6 Implementation

Installing solar PV pumping solutions in this community has several benefits for farmers. First of all, the community farmers will get a new energy system that will help them improve their access to water for irrigation, thereby generating more income opportunities by complementing staple foods with high-value crops. Secondly, it helps reduce manual work and improve time expenditure. Thirdly, it helps improve crop yields, increase incomes, and enhance crop resilience and food security. In addition to the direct benefits to the farmers in Karshi-Abuja, this project, if successful, will be a model that can be used in communities throughout Nigeria.

6.1 Recommendation

- Farmers should work together to invest and share responsibility. If everyone agrees, they can use SPIS systems to get money to start a business, especially poor farmers. It will also allow group members to share costs and risks, benefit from economization of input purchases and marketing expenses, and foster knowledge sharing.
- More research is needed to compare the economic viability of solar water systems and diesel-driven pumping systems in rural communities in Karshi-Abuja.

7 Conclusion

The design for a PV-powered water pumping system for drip irrigation is presented. The focus is on determining how much water a crop needs daily, and choosing a PV array that will power a water pump to lift water from a well to a storage tank. Water demand for crop irrigation in Karshi was discovered to be 10,000 L per day for a field size of 1 ha. A good match between the pump and PV module(s) was considered in order to ensure efficient system operation. A pump that has the capacity to supply a flow rate of 2.4 m^3/h at a TDH of 14.2 m was selected (a Lorentz PS2-150 C-SJ5-8). After analyzing the pump curves, it was found that the pump motor requires about 258 W of power to achieve the desired performance. After studying the manufacturer's specifications, it was observed that the motor has an input voltage range of 17 to 50 volts DC and a maximum current draw of 18 A. After reviewing various solar panels on the market, a solar panel with the appropriate configuration was chosen (peak power of 50 W, operating voltage of 17.7 V, and operating current of 2.8 A). The power generated by the three 110-watt solar panels wired in parallel effectively powered the submersible pump. The pump delivers approximately 40 L of water per minute from the well to an elevated water storage tank. This designed system can provide a consistent power source for irrigation pumps, enabling farmers to optimise water usage and increase crop yields. Therefore, it is suggested that a pilot be run in Karshi to see if it works and then scale up to the rest of Nigeria.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

VA: Conceptualization, Methodology, Writing – original draft.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author declares that no Gen AI was used in the creation of this manuscript.

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Appendix A

TABLE A1 Friction loss in plastic pipe with SIDR chart.

Flow rate		Pipe diameter											
[Gal./min]	[l/min]	½	¾	1	1 ¼	1 ½	2	2 ½	3	4	5	6	In nominal
		0.66	0.82	1.05	1.38	1.61	2.07	2.47	3.07	4.03	5.05	6.06	In actual
1	3.8	1.0	0.40	0.10	0.02								
2	7.6	3.0	1.20	0.40	0.10	0.05							
3	11	6	2.30	0.70	0.20	0.10							
4	15	10	4.00	1.20	0.32	0.15	0.05						
5	19	16	6	1.80	0.48	0.23	0.07						
6	23	22	8	2.50	0.70	0.32	0.10	0.04					
7	27		11	3.20	0.90	0.43	0.13	0.06					
8	30		13	3.90	1.10	0.50	0.16	0.07					
9	34		16	4.90	1.30	0.60	0.19	0.08					
10	38		19	6	1.60	0.80	0.24	0.10	0.04				
11	42		23	7	1.90	0.90	0.28	0.12	0.04				
12	45		26	8	2.20	1.00	0.30	0.14	0.05				
14	53			11	2.90	1.40	0.40	0.18	0.06				
16	61			14	3.70	1.80	0.50	0.23	0.08				
18	68			16	4.50	2.20	0.70	0.28	0.10				
20	76			20	5.40	2.60	0.80	0.34	0.12	0.03			

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