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Research Article

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In Situs Efficiency of a Direct Coupled Photovoltaic Irrigation System in Rural Niger, Input Current Oversizing Effect on The Pump Efficiency

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Abstract
A photovoltaic irrigation system, an excellent example of the water-energy-food nexus, is a suitable system for farmers in the semi-arid countries of the Sahel. These systems align with UN Sustainable Development Goals (SDGs), addressing food security, water access, and sustainable energy. However, their efficiency depends on mastering configuration, installation, and operation, crucial for resource conservation and optimal performance. This study evaluates a direct-coupled PVWPS in rural Niger found the PV array was oversized by double. Indeed, exceeding pump manufacturers' specifications by increasing PV array capacity didn't notably improve performance but decreased pump efficiency. For instance, with a 1.5 kWp PV array, the pump flow rate reached 3.5 m3/h. Doubling (100% increase) the PV capacity to 3 kWp marginally increased the maximum flow rate to 4.2 m3/h, yielding only a 20% water flow increase. This underscores the importance of appropriately sizing PV arrays to avoid diminishing returns. These findings are crucial for decision-making in designing and implementing sustainable photovoltaic water pumping systems. Optimizing PV array configuration based on pump specifications can enhance system efficiency and longevity, advancing sustainability goals while conserving resources.

Keywords: Solar Photovoltaic, Pumping System, Energy Efficiency, Water-Energy-Food Nexus, SDGs

Abbreviations

Latine:

ANERSOL	National Agency of Solar Energy
C	Vacuum velocity of light
E	the input irradiance
g	gravitational acceleration
h	the Planck's constant
H	the manometric head
I	*Current*
I	then load current
I_{inp}	pump input current
I_L	the photovoltaic current,
I_0	the reverse saturation current
P_{inp}	Pump power consumed
P_m,	Maximum PowerPoint
Pp	hydraulic power output
PVWPS	Photovoltaic water pumping system
q	electronic charge,
Q	Output flow rate of the pump
Rn	Reynold's number
R_S	series resistance,
R_{SH}	parallel resistance
SI	
SPVWPS	
T	absolute Temperature,
TMH	
TMH	
$u\nu$	the spectral energy density
v	the mean flow velocity
V	Voltage
V_{OC}	Open circuit Voltage
V_{inp}	pump input voltage

Greek

ΔP	
ΔPl	Linear losses
ΔPs	Minor or Singular Losses
η	energy conversion efficiency
ν	the light wave frequency
λ	the flow coefficient, also called the Darcy friction factor
ρ	density of water

1. Introduction

Agriculture is the pillar of most African economies. According to World Bank data, from 1960 to 2018, Niger's agriculture sector contributed approximately 40% to the gross domestic product (GDP) Global Economy [1]. Also, 84% of its population living in rural areas is actively involved in crop production Cossi and Issoufou [2]. In Niger, like in some West African countries, rural communities depend on subsistence farming and livestock breeding. Climate Change's effect on agriculture further endangers food security, especially in Sahelian countries. It is, therefore, crucial to look for alternative solutions for farming while protecting the environment. Powering irrigation systems with solar energy is reliable and ecologically sustainable and can improve rural livelihoods. However, many farmers rely on diesel for their water pumping needs Hiller et al. [3].

Even though diesel generator pumping systems are capable of high output, their fuel consumption leads to very high operational costs too often beyond the users' ability to pay James et al. [4]. Using diesel or propane-based water pumping systems requires expensive fuels and creates noise and air pollution Chandel et al. [5]. The operation and maintenance cost and replacement of a diesel pump are 2–4 times higher than a solar photovoltaic (PV) pump. In contrast, solar pumping systems are environmentally friendly and require low maintenance with no fuel cost. Therefore, using solar power technologies for water pumping applications is an alternative to address manual and diesel pumping limitations. On the other hand, only 0.4% of Niger's rural population is connected to grid electricity USAID, while the average daily global horizontal irradiation range is 5.81 to 6.58 kWh/m2/day Global Solar Atlas [6, 7]. Given this shortage of grid electricity in remote areas, a solar-powered irrigation system may be an appropriate alternative for farmers in the rural area of Niger.

In 2019, a solar PV water pumping system was installed in Djami (village of Bonkoukou) for irrigation purposes as a demonstrator site of the interdisciplinary Climate information for Integrated Renewable Electricity Generation (CIREG), a Germany-supported institution. The installed PVWPS works and is beneficial to the users. However, the installed system's efficiency assessment can help reduce water and energy loss and drive a suitable solution for efficient use.

Efficiency in water pumping system for irrigation can be at a different level of a PVWPS, such as the Photovoltaic (PV) array efficiency (power provided by the panels to the pump) and the pump efficiency (Sub-system).

Worldwide, some studies have been undertaken to evaluate the performance and efficiency of photovoltaic water pumping systems [8-13]. These studies assessed both the technical performance and economic viability of photovoltaic pumping systems for water supply purposes, both for domestic and irrigation water. However, in line with the study objective, Table 1 highlights some successful applications of solar pumping systems' performance evaluation on direct-coupled photovoltaic water pumping.

Though, to the best of our knowledge, limited studies have been carried out on solar pumping systems installed in the field in rural Niger. Additionally, since the CIREG demonstrator site (PVWPS) was implemented in 2019, no study has been conducted to evaluate its efficiency. There is a clear need to evaluate the PVWPS efficiency to improve and assist in future decision-making on designing and implementing a photovoltaic water pumping system.

1.1. Performance Evaluation of the Photovoltaic Water Pumping System

Efficiency in water pumping systems can be at a different level of a solar photovoltaic water pumping system (PVWPS), such as the Photovoltaic (PV) array efficiency (energy proved by the panels to the pump) and the pump efficiency (Sub-system).

There are two significant parts of a solar PV water pumping system (SPVWPS): The Solar Photovoltaic array and the entire pumping components (controller and pump). Therefore, the efficiency of the SPVWPS could be evaluated at these two levels, as shown in Figure 1.

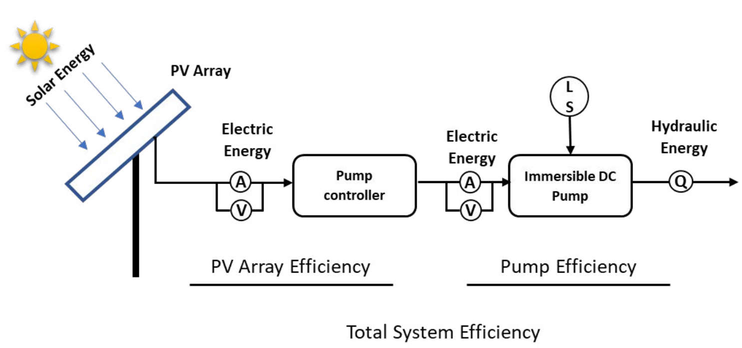

Figure 1: Experiment (Sensors Connection) Scheme

- A to measure the pump input current
- V to measure the input voltage of the pump
- LS to measure the water level in the borehole
- Q to measure the quantity of water drawn by the pump

Reference no.	Country	Application	Objective	Research findings
Mohanlal K and Joshi JC[14]	Egypt	Irrigation	performance of a PV-powered dc permanent-magnet (PM) motor coupled with a centrifugal pump analysis at different solar intensities and corresponding cell temperature	System efficiency is increased up to 20% by manually sun-tracking three-time in a day compared to the fixed tilted PV array.
Gad [9]	Egypt	Domestic water supply	performance predicting of a direct-coupled photovoltaic water pumping using a computer simulation program (MATLAB version 7.0)	Hourly performance of the system was simulated for different orientations of photovoltaic panels and found the efficiency of 13.86% in winter and 13.91% in summer
Mokeddem et al. [12]	Algeria	Irrigation and Domestic	Investigate the performance of a directly coupled DC-powered PV water pumping system.	Even thus, motor-pump efficiency did not exceed 30%, the system's efficiency can be increased by selecting the size of the PV array, its orientation and the motor-pump system.
Khan et al. [15]	Bangladesh	Rural water supply	Design and performance analysis of water pumping using solar PV	System efficiency is increased by adding a DC-DC buck converter for a direct-coupled PV water pumping system.
Tomas et al. [16]			Efficiency optimisation of the standalone photovoltaic water pumping system	An implementation of MLPT in addition to MPPT would increase pump output in a nearly constant solar radiation environment(Tomas Perpetuo Correa, Seleme, Issac Seleme Jr, Selenio Rocha Silva., 2012).
Atlam and Kolhe [17]	Turkey	Domestic	Performance evaluation of directly photovoltaic powered DC PM	System performance and efficiency can be improved by matching the output characteristics.
Onur et al. [18]			development of a low-cost solar-powered Drip irrigation model	The increase in temperature of solar PV panels doesn't affect overall system efficiency. But due to an increase in available solar radiations, the divergence in MPPT would be observed. This divergence can be avoided through MPPT controllers.

[11]	India	Irrigation	Performance Assessment of Solar Agricultural Water Pumping System	
Abass [8]	Niger	Domestic	Impacts of local environmental and weather conditions on the performance of the solar PV panels, pumps and batteries	Incorrect sizing of solar pump according to the depth of the borehole leads to a low-efficiency rate (up to 50%).

Table 1: An Overview of Successful Applications of Solar Pumping Systems Performance Evaluation

The solar PV water pumping systems' efficiency can be explained through the mathematical equations below described [19-21].

1.1. Photovoltaic (PV) Panels' Efficiency

The efficiency of the photovoltaic (PV) panels shows how the solar energy contained in the sun's rays is converted into usable electricity by the solar cells in the solar panel. In other words, it is the ratio of the electrical power produced by the solar modules to the solar radiation incident on the total surface of the modules. This efficiency depends mainly on the quality and nature of the material used to manufacture the solar cells.

$$\textit{PV Array efficiency} = \frac{\text{Power output of the Array}(W)}{\text{Array Power Input }(W)} \quad \text{Eq (1)}$$

1.2. Pumping Efficiency

The pump hydraulic efficiency is the ratio between the hydraulic power used to pump a volume of water through a given height to the solar system's output power. The following formula is the expression of the pump hydraulic output (Pp):

$$Pp = \rho g Q H \quad \text{Eq (2)}$$

Were,

- P_p, hydraulic power output of the pump in W
- H, the manometric head consisting of static head, friction losses and velocity head in meters (m)
- Q, Output flow rate of the pump in m^3/s
- ρ, density of water
- g, gravitational acceleration (9.81 m/s^2)

$$\textit{Pump efficiency} = \frac{\text{Hydraulic power }(W)}{\text{Array Power output }(W)} \quad \text{Eq (3)}$$

Total (system) efficiency indicates the extent to which the overall system converts solar radiation into water at a given head.

$$\textit{System efficiency} = \frac{\text{Hydraulic power }(W)}{\text{Array Power Input }(W)} \quad \text{Eq (4)}$$

2. Materials and Methods

The solar PV water pumping system subject of this study is located in Djami, a rural community of Bonkoukou located at 14,017N latitude, 3,217E longitude, 140 km North-East of Niamey, Niger. The primary income of this rural community is based on agriculture, livestock and small-scale irrigated horticulture. Water for horticulture irrigation is mainly pumped or fetched by diesel pumps, electric pumps driven by a diesel generator, and hand pumping

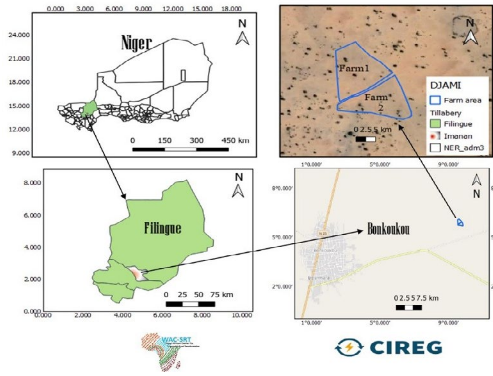

Figure 2: Map of the Study Area

Figure 2 is a general map that presents the study area and the localisation of the farm on which the horticulture water pumping system is installed. The climate has very hot summers and mild or warm winters, and it cannot support forests or extensive vegetation because of limited precipitation (Moll, n.d.). Over the year, the average temperature in Bonkoukou is 29.5°C, with an average rainfall of 635.3 mm per year [22].

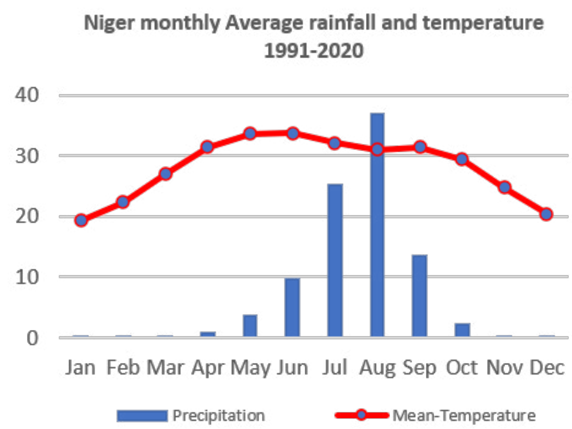

Figure 3: Niger Monthly Average Rainfall and Temperatures 1991-2020 (World Bank Data)

2.1. Description of the System

The solar pumping system installed at Djami in Bonkoukou village is intended to supply water for domestic usage. The system consists of 12 PV modules, each with a capacity of 250 Wp. These PV modules convert incident solar radiation into direct current to power the electric SQFlex motor pump, controlled by the CU 200 pump controller. The motor pump is situated at a depth of 45 meters within a well. It has a power rating of 1.4 kW and operates within a wide voltage range in both DC and AC. The water pumped by the SQFlex motor pump is stored in a tank approximately 9 meters above ground level, with an average volume of 30 m3. From the storage tank, water is distributed through gravity via a water distribution network for farming purposes, bringing water close to the irrigation farm. To mesure solar irradiance and ambient temperature, a pyranometer and temperature measurement sensor, respectively, were utilized at a meteorological station. Data collection occurred every 30 minutes from 7:30 AM to 6:30 PM from August 3rd to August 29th, 2020. Additionally, a multimeter equipped with a clamp (Fluke 736) was employed to measure the output voltage and current of the PV generator. The power supply to the helical rotor pump was obtained from the display unit of the CU 200 controller.

2.2. Experiment Running and Data Processing

The study is based on quantitative methods and focuses on field data collection on the direct coupled solar photovoltaic water pumping system using specific measurement tools for each part of the system. Two series of experiments were conducted, as illustrated in Table 2.

• The first on the installed PV farm (250W x 6 x2) with a total capacity of 3 kW from 03 to 12 July 2020 (Otherwise two series of six modules).
• The second with a PV string of 1.5kW (6 PV modules of 250 W each in series) from 27 to 29 July.

The second experiment was conducted to assess the pump output with 1.5kW since the manufacturer gives 1.4kWp as the rated peak power for the used pump (SQ Flex 3A-10).

N°	Date	start	End	Duration (hours)	Number of data	Flow Range (m3/h)	Dynamic Head Range (m)	Losses Head Range (m)	Total Head Range (m)
Summary of the first field experiment data									
1	03.07.2020	7:30 AM	6:30 PM	11	22	3.8	18.4	15.0	33.4
2	04.07.2020	7:30 AM	6:30 PM	11	22	3.3	18.1	11.3	29.5
3	05.07.2020	7:00 AM	6:30 PM	11,5	23	3.8	18.3	15.0	33.2
4	06.07.2020	7:00 AM	6:30 PM	11,5	23	3.9	18.4	15.8	34.1
5	07.07.2020	7:00 AM	6:30 PM	11.5	23	4.0	18.3	16.6	35.0
6	08.07.2020	7:00 AM	6:30 PM	11,5	23	3,6	18,2	13,5	31.7
7	09.07.2020	7:30 AM	6:30 PM	11	22	4.0	18.4	16.6	35,0
8	10.07.2020	7:00 AM	10:30 AM	3.5	7	3.1	17.9	9.7	27.6
		1:30 PM	6:30 PM	5	10				
9	11.07.2020	7:30 AM	6:30 PM	11	22	4.0	18.4	16.6	35.0
10	12.07.2020	7:30 AM	3:30 PM	8	16	3.9	18.5	15.8	34.3
		Total of data			**213**	**Median Total Head Range**			**34**
Summary of the second experiment fields data									
11	27.07.2020	7:30 AM	2:30 PM	7.0	14.0	3.1	17.9	10.0	27.9
12	28.07.2020	9:00 AM	6:30 PM	9.5	19.0	2.2	17.6	5.0	22.6
13	29.07.2020	7:30 AM	6:00 PM	10.5	21.0	2.9	17.8	8.1	25.9
		Total of data			54,0	Median Total Head Range			26

Table 2: Summary of the Experiments

The pump's prevailing input (I and V) at the pump controller (CU200) output was measured and recorded every 30 minutes from 7:30 AM to 6:30 PM during the experiment days. The water level in the borehole and the main water meter's index were recorded simultaneously with the pump inputs.

It was also measured at the outlet of the PV array every ten (10) minutes the Short Circuit Current (Isc) and the Open circuit voltage (Voc) of a day to evaluate the PV panels' efficiency. The Isc and Voc measurement was done every ten minutes because the climate data is also measured every ten minutes at the chosen weather station.

N^0	Equipment	Parameters
1	Solar Photovoltaic capacity	3 kWp
2	Submersible pump	Grundfos SQ Flex 3A-10 / installed at 45 m in the borehole
	Borehole	Depth: 80 m / Static Water Level: 7.74m
3	Water reservoir	30 m^3
4	Static water head	16.75 m

Table 3: Overview of the PVWPS Components

2.2.1. Climate Data (Solar Irradiance and Temperature)

To measure the climate data such as global solar irradiance and temperature, the weather station of CHICAL was used. The data of this station was used due to its position in the study area, it is indeed the closest climate data station, which gives observation data. The weather station is located at 3.2649° of longitude East and 14.1509° of latitude North; it measures the climate data every ten (10) minutes of the day.

However, the weather station of CHICAL measures the solar radiation on the horizontal plane, while the PV panels of the PVWPS are sloped 15°. Thus, the solar irradiance data was cross-checked using the National Agency of Solar Energy (ANERSOL) permanent data record in Niamey.

2.2.2. Pump Inputs Measurements

The pump's power input (Pinp), the PV panels output, was measured every thirty minutes with the digital multimeters Fluke 115 C and recorded in a designed table.

N°	Instrument	Accuracy
1	Clamp meter Fluke 374 **Measurement** Direct Current (I)	1.5% ± 5 digits (20 – 500 Hz)
2	Digital multimeter Fluke 115C **Measurement** DC Voltage (V)	1.0% + 3 (DC, 45 Hz to 500 Hz) 2.0% + 3 (500 Hz to 1 kHz)
3	Digital multimeter Victor VC890D **Measurement** Direct Current (I) DC Voltage (V) **Observation** Used for Fluke 374 and 115C accuracy checking	DC Voltage ±(0.5%+3) DC Current ±(0.8%+10)
4	Water level sensor OTT KL 010 **Measurement** The water level at each pumping head **Observation** used to identify the water level in the borehole	±0.5% of the measured value, min. ±2 S/cm
5	Flow water meter (32 mm), multiple jet dial class A, ISO 4064 certified **Measurement** Quantity of water pumped **Observation** placed at the pump's outlet to record the amount of water pumped in the tank each hour	Qt_{min} ± 5% Qt_{max} ± 2%
6	WASCAL Climate weather station N^0 2717014 **Measurement** Solar irradiance and temperature	

Table 4: List of Materials

The power (P_{inp}) was computed using the following formula based on the record data.

$$Pinp = Iinp \times Vinp \qquad (5)$$

Where: Pinp is the power consumed by the pump; Iinp is the pump input current; $\mathbf{V}_{inp}$ is the input voltage of the pump.

Total Manometric Head (TMH) Measurement

The total manometric head is the difference in pressure (in meters) between the pump's inlet and outlet points. The TMH was computed for each given running power of the pump using the following formula [23].

$$TMH = TPH + \Delta P \qquad (6)$$

It takes into account the two components:
(i) The total pumping head (TPH) or total height between the down draw point and the highest point of discharge.
(ii) Pressure losses (ΔP) as a function of flow rate, pipe diameter over the length and hydraulic network configuration.
The total pumping head (TPH) was measured simultaneously with the pump input using the borehole water level sensor OTT KL 010. The values were recorded and used to calculate the total head of the pumping system at each measurement. The pressure loss (ΔP), or drop, can be Linear (or regular), referring to the friction of the fluid against the internal wall of the pipe over a length *L*. And when the pressure loss is Singular (or local), it is due to singularities (abrupt change in diameter, change of direction, taps).

Linear Losses (ΔPl)

In a cylindrical pipe of uniform diameter D, flowing full, the pressure loss due to viscous effects Click or tap here to enter text., Δpl is proportional to length L. The Darcy–Weisbach equation can characterise it:[23]

$$\frac{\Delta Pl}{L} = \lambda \times \frac{v^2}{2D} \qquad (7)$$

where the pressure loss per unit length Δpl/L (SI units: Pa/m) is a function of:

• D, the hydraulic diameter of the pipe (for a pipe of circular section, this equals the internal diameter of the tube;

• v, the mean flow velocity, experimentally measured as the volumetric flow rate Q per unit cross-sectional wetted area (m/s);

• λ, the flow coefficient, also called the Darcy friction factor.

The flow coefficient (λ) is determined based on the flow type; in our case, the flow is Laminar.

In fluid mechanics, laminar flow is the mode of flow of a fluid where all the fluid flows more or less in the same direction [24]. In Laminar flow, λ can be calculated with Poiseuille's equation below.

$$\lambda = \frac{64}{Rn} \qquad (8)$$

Where Reynold's number (Rn) < 2000 since it is a laminar flow type, the value of the flow coefficient (λ) is, therefore, 0,32.

From the equation, the linear losses can be expressed as follow :

$$\Delta Pl = \lambda \times \frac{v^2}{2} \times \left(\frac{L}{D}\right) \qquad (9)$$

With: λ =0.32; L= 137.5; D=56.6 mm, and V to be calculated for each flow rate using the following formula:

$$v \times A \longrightarrow v = \frac{Q}{A} \text{ with}$$

$$A = \pi \times r^2 \longrightarrow v = \frac{Q}{\pi \times r^2}$$

Where: A is the cross-sectional area at a point in the flow path; r is the radius, and v is the velocity of the liquid.

Minor or Singular Losses ΔPs

Fittings such as elbows, tees, valves, and reducers represent a significant component of the singular pressure loss in most pipe systems [25]. The singular losses are any head loss present and the head loss for the same length of straight pipe. Like pipe friction, these losses are roughly proportional to the flow rate's square and can be expressed through the equation below [26].

$$\Delta Ps = \sum K \frac{v^2}{2g} \qquad (11)$$

K is the loss coefficients in the length of pipe, each contributing to the overall pressor loss.

Although K appears to be a constant coefficient, it varies with different flow conditions. Factors affecting the value of K include:

• the exact geometry of the component in question
• the flow Reynolds Number
• proximity to other fittings

There are many tabulations of K-values and methods for calculating K-values. However, Table 4 reports typical K-values for various fitting types.

Four standard 90° Elbow Curves mean the loss coefficient is 0,75.

Fitting	Types	K
45° Elbow	Standard (R/D = 1)	0.35
	Long Radius (R/D = 1.5)	0.2
90° Elbow Curved	Standard (R/D = 1)	0.75
	Long Radius (R/D = 1.5)	0.45
90° Elbow Square or Mitred		1.3
180° Bend	Close Return	1.5
Tee, Run Through	Branch Blanked	0.4
Tee, as Elbow	Entering in run	1

Table 5 : K-Values for Various Types of Fitting [27].

The pressure loss (ΔP) for each given TMH was calculated by summing the linear losses(ΔPl) with the singular losses(ΔPs).

3. Results and Interpretation.

3.1. PV Output and Efficiency

The power production of a PV system depends on solar irradiance. Many studies argue that the output power of the PV module production depends mainly on the solar irradiance [27, 28, 13, 30]. Efficiency is the most commonly used parameter to compare one cell/module's performance to another. Figure 4 shows the Installed PV array fields efficiency measure based on the solar radiation received in the area. It must be underlined that the solar irradiance measurement is carried out far from the solar panels' field (i.e., at Chical, at about 25 km of the field experiment of Djami). Nevertheless, this fact does not impact the data quality, as seen in Figure 4. The observed PV efficiency is somewhat higher than 10%, the lower and highest obtained efficiencies are in red, and the average efficiency is in green. However, this needs to be definite with more accurate solar measurement.

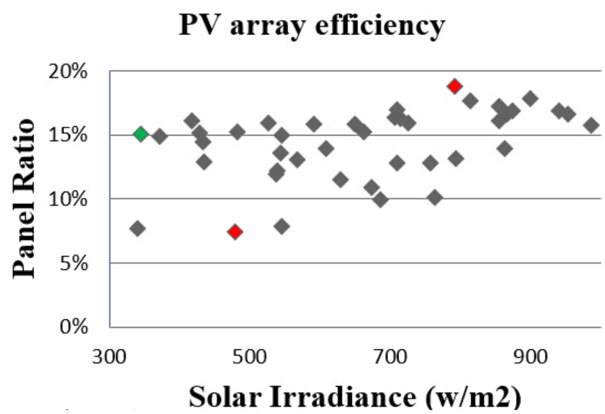

Figure 4: Installed Photovoltaic Array Efficiency (12/07/2020)

The installed system produced a maximum power of 3.1 kW from the panels at 940 W/m2 of solar radiation around midday. It is observed in Figure 5 the relation between solar irradiance and PV out during the day.

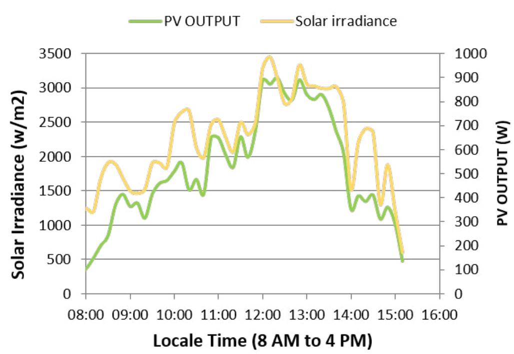

Figure 5: Variation of PV Output with Solar Irradiance

3.2. Pump Efficiency

The relation between incident solar irradiance and water output of the installed system is presented in Figure 6. It can be noticed that the pumped water flow is roughly independent of the solar radiation above 700 W/m².

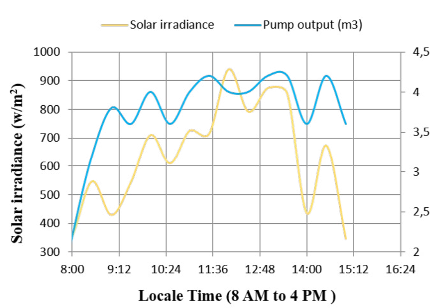

Figure 6: Variation of Solar Irradiance with Pump Output (m3)

3.2.1. Experiments with a PV Array of 3kWp

Based on the data collected during the first experiment, it is noticed that the total height of the average data, in this case, is 34 m. Therefore, the total height that could be considered according to the manufacturer's diagram is 35 m. The correspondent 35 m height data provided by the manufacturer for the installed pump is used.

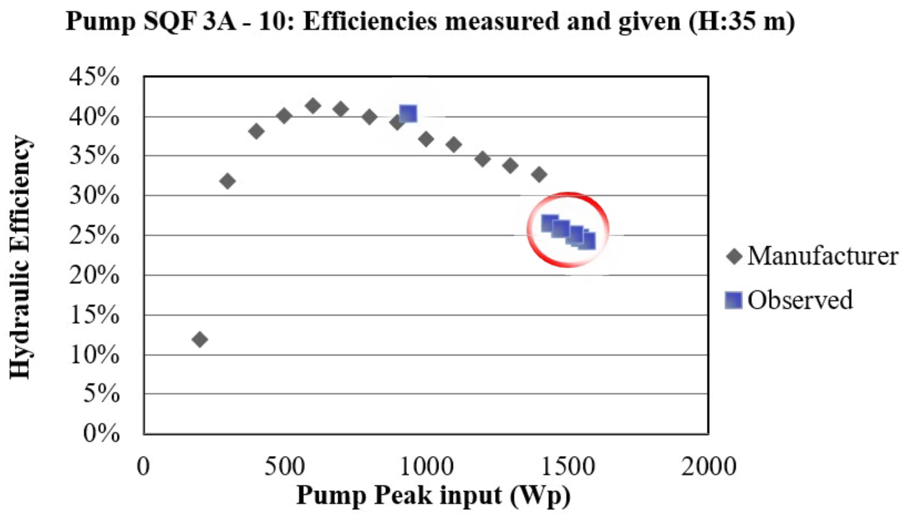

Figure 7: Efficiency Measured for PV 3k WP and given (by the Manufacturer) of the Pump

The maximum peak power value given by the manufacturer for this pump is 1.4 kWp, and its optimum efficiency for 35 m head is between 34% and 41%. Figure 7 shows that majorities of efficiencies measured are less than optimal values given by the manufacturer.

It is also observed in Figure 7 that the highest optimal efficiency (given by the manufacturer) is achieved at 600 Wp, while the efficiency decreases when the pump consumes over 900 Wp. The topmost efficiency(40%) measure on the field was observed at 937 W, and all the other efficiencies are about 25% because the input power is higher than 1.4 kWp.

While looking at the output parameter of the pump controller (CU200), it noticed that there is skimming off the electric current as illustrated by Figure 8.

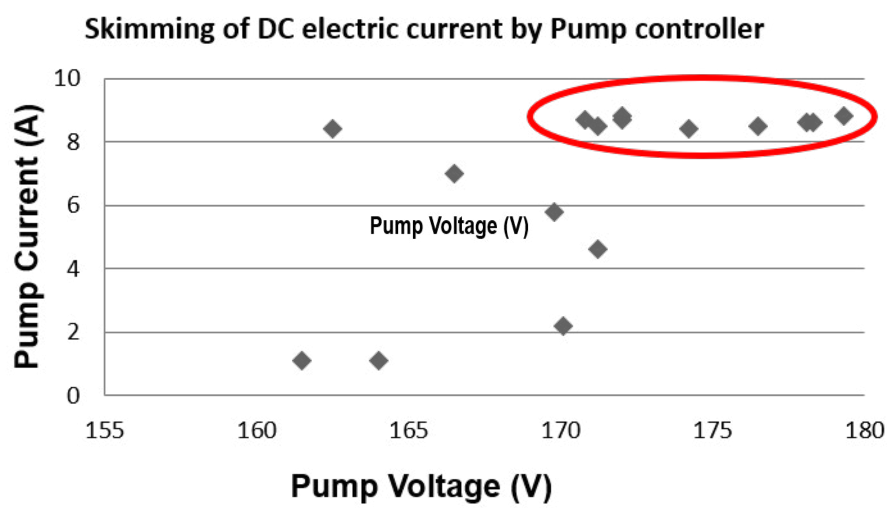

Figure 8: Skimming of DC Electric Current by Pump Controller CU200

Figure 9 describes the gaps between the PV panels' generated current, and the pump's consumed current. Although produced current increases up to 15.90 A, almost twice the required pump current (from 10:30 AM to 2:00 PM), the pump input current is limited at around 8,4 A (skimming off) for the same period.

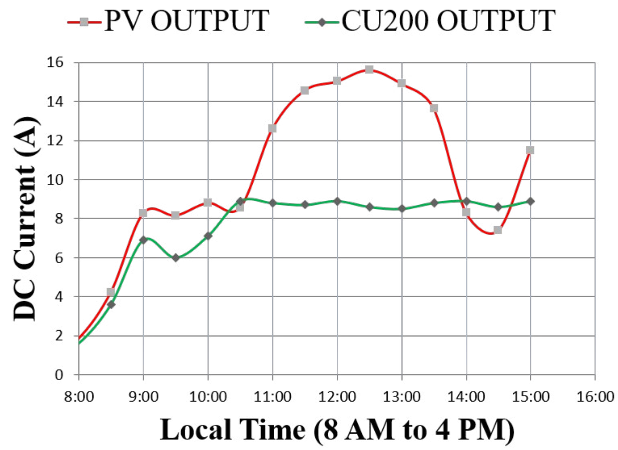

Figure 9: PV Output and Pump Input Variation (12/07/2020)

3.2.2. Experiments with a PV array of 1.5kWp

This experiment is inspired by the previous undertake from 03 to 12 July 2020, in which it was noticed that the PV farm was oversizing according to the manufacturer pump (SQF 3A-10) characteristics. The installed PV farm capacity also leads to high PV power generation that is less usable for the pump.

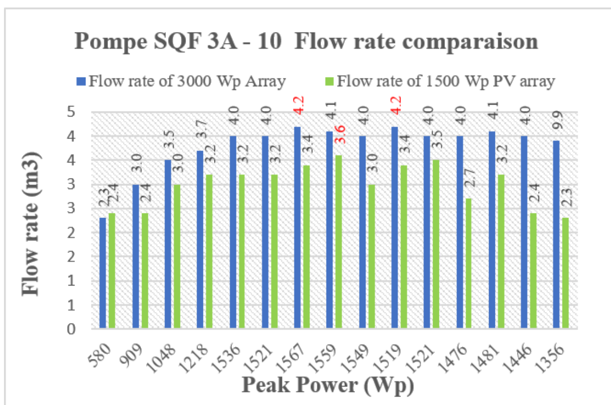

Figure 10: Presents the Manufacturer, Optimum Efficiency Range, and the Field Measured Efficiency with a PV farm Capacity of 1.5 kW

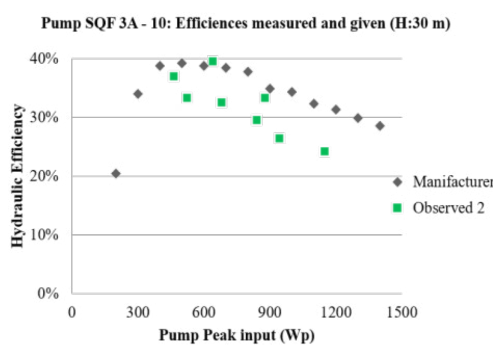

Figure 10: Efficiency with PV Farm of 1.5 kWp

The data analysis revealed that the total height of the median data is 26 m; therefore, the manufacturer data corresponding is 30 m height which facilitated the installed pump assessment. The results of the second experiment revealed that most of the computed efficiencies are over 30% and close to the manufacturer's standard for 30 m height.

Figure 11 presents the pump impedance obtained during the experiment; all electric current values are lower than 8.4 A, the maximum pump current.

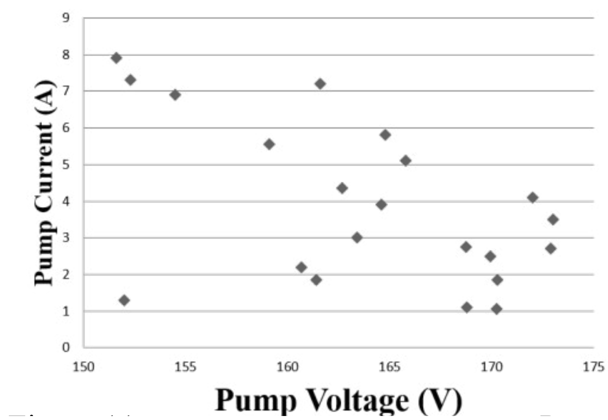

Figure 11: Pump Impedance Voltage (V) VS Current (A) Experiment 2

The optimum given (by the manufacturer) efficiency at different total heights and the average measured efficiencies of the two experiments is presented in Figure 12.

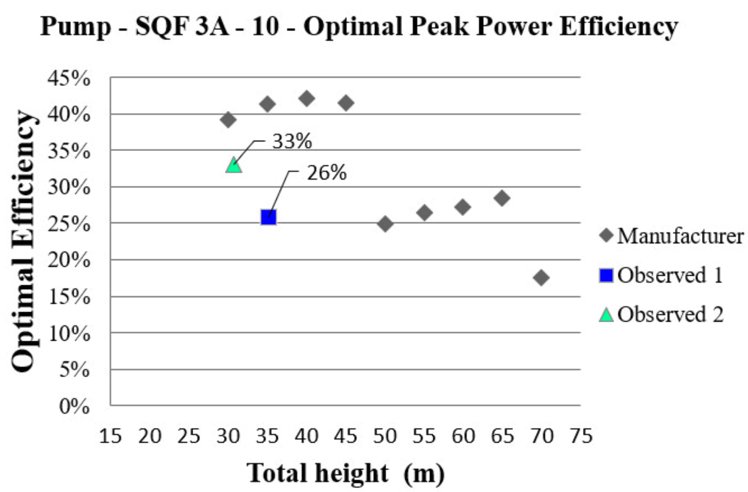

Figure 12: Comparison of the Measured Efficiencies at Different Heights

It can be noticed in Figure 12 that :

• The average efficiency obtained during the first experiment (with the PV array of 3 kWp) at 35 m of height is 26% though the given optimum efficiency for the same height is 41%. This means a loss of 14% of efficiency compared to the optimum.

• In the second case (experiment with the PV array of 1.5 kWp), the average measured efficiency for 30 m height is 33%, whereas the given optimum efficiency for the same height is 39%.

The installed pump is more efficient in the 1.5 kWp photovoltaic arrangement than in a 3 kWp photovoltaic scheme. Therefore, the configuration of the photovoltaic installation does not allow a high SPVWPS efficiency, but it could be more efficient with a suitable configuration. Furthermore, Figure 13 shows a slight difference between the hourly pump flow rate in the two cases.

In detail, with the PV array of 1.5kWp capacity, the pump flow rate increases up to 3.5 m3/h. In contrast, the maximum pump flow rate with a 3 kWp PV array capacity is 4.2 m3/h, which leads to an improvement of 20% of water flow for an increasing energy supply of 100%.

3.3. Analysis and Discussions of the Results

The PV array efficiency assessment results (Figure 4) show that the average efficiency is 15%, and the efficiency obtained at the higher solar irradiance (987w/m2) is 14%. These results are in harmony with and statements on commercial polycrystalline PV efficiency which should be between 14% to 16% [31, 32]. While there are some field efficiencies up to 17% and even one up to 19%, the results are also in line with and articles which report that polycrystalline efficiencies are below 20% [28, 29]. However, the results of the measured efficiencies are not accurate enough because the solar irradiance (SI) was not measured at the surface of the panels but through a weather station measuring the solar irradiance at 2 to 3 m from the soil and far from the panel's field (at Chical, some 25 km from Djami). The pump's flow rate gradually increased as the solar irradiation increased, peaking at about 4.2 m3/hour and decreasing when the solar irradiation power decreased, as described in Figure 6. This result is similar to those of Otieno and Hossain, who observed that the pump discharge increased with an increase of solar radiation to its peaking and then decreased gradually as solar radiation decreased [13, 33].

Lower pump efficiencies observed during the first experiment are related to the high power used to run the pump (Figure 7). Indeed, reported that higher pumping power implies a significant decrease in pump efficiency by 90-70% [34, 35]. Also, argues that the decrease in pump efficiency is also induced by an increase in its input power. The pump controller's (CU200) ability to provide only the necessary operating capacity to the pump even though it receives higher direct current from the PV generators (Figure 9) could justify the skimming of current and its output (Figure 8).

Achieving the best efficiencies during the second experiment was possible due to the pump input power in line with the manufacturer's instructions (Figure 10). It was also observed that as far as the pump input power is getting high, the pump efficiency decreases. Besides, the second experiment shows that there is no controller (CU200) output current skimming (Figure 11). And this could be explained by the fact that the PV output currents did not exceed the maximum current needed by the pump, as here, the system operates on a 1.5 kW PV farm configuration.

Conclusion

This study evaluated the solar pumping system's efficiency with two experiments; the first experiment had a 3kWp PV array capacity, higher than the pump requirement, leading to low pump efficiency. The second experiment with a PV capacity of 1.5kWp close to the correspondence pump requirement leads to high pump efficiency. Altogether, the efficiency evaluation of the pumping system operating under varying real environmental and climatic conditions is crucial for optimal sizing and design. Increasing the number of PV modules (i.e., electric-current oversupply) powering the pump does not result in higher flow rates but decreases pump efficiency. This information is crucial for engineers and would help to save considerable capital investment in a solar PV water pumping system [36-40].

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Author Contributions

All authors contributed to the study's conception and design. Methodology and Materials preparation were performed by Segbedji FAVI, Boubacar IBRAHIM, Saleye YAHAYA and Rabani ADAMOU. Segbedji FAVI undertook data collection while data analysis was performed by Segbedji FAVI, Saleye YAHAYA. Supervision: Boubacar IBRAHIM and Saleye YAHAYA. Segbedji FAVI wrote the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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