International Journal of Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2023.9.9.5

Volume 9, Issue 9
September - 2023

Assessment of Performance of Solar Powered Direct Current (D.C) Water Pumps for Boreholes in Kaduna and its Environs

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ABSTRACT

Irregular power supply and frequent grid failure are regular phenomenon in Kaduna metropolis. The use of photovoltaic array for water pumping system is one of the most promising techniques in solar energy applications. Deployment of PV based solar pumping system for domestic applications is a viable alternative to replace conventional grid electricity .In this studies, theoretical design, performance and simulation analysis of PV based water pumping system in some selected area of studies in Kaduna with the use of the computer software package PVSYST 7.4.2 version is carried out. The purpose is to evaluate the performances of photovoltaic pumps in the selected boreholes in the studies areas. According to the analysis, the solar water pumping system has an average system efficiency of 57.9 %. Which is in fair agreement with the previous literature, it was concluded that solar water pumping system should be strongly recommended for both urban as well as rural water supply system.

Keywords: Boreholes, Irradiance, Performance, Pumps Photovoltaic, Solar System.

1. INTRODUCTION

Scarcity of electricity is one of the major plights in the growth of rural areas in most states in Nigeria. The application of solar source of energy has augmented in the rural areas owing to shortage and high cost of electricity. The applications of photovoltaic water pumping system will enhance technological and socio-economic development. It is a reliable solution to the present day energy crisis in our nation. The system is easy to implement and friendly to the environment. It requires minimal maintenance and attention, has zero fuel cost, possesses high reliability and releases no emissions. Solar energy is a green way for energy production; it provides free energy when an initial investment is made [1]. It is natural, renewable, and easily convertible to other forms and could be stored for further use if the need be. Renewable energy does not contaminate the surroundings and it also encourages energy production from locally available resources. Consequently, amid all renewable sources of energy, solar photovoltaic energy is acknowledged as the cleanest and most dependable source of alternative power [2].

Regular water supply system from Kaduna state water board has become a source of worry to most residents within the state and its environs. Most residents rely on regular supply from boreholes dug from personal efforts to alleviate the inconsistency in supply. However the supply of power to operate the submersible pumping machine is another major obstacle that needs to be addressed, this simply due to irregular supply of electricity from Kaduna Electricity distribution company (KEDSCO) because of low grid power coverage in the state. Hence, photovoltaic cell will be employed to provide an alternative source for energy for powering the submersible pump in the provision of clear, affordable drinking water and also for normal domestic chores within the metropolis.

2. LITERATURE REVIEW

Interestingly, research and development work in renewable energy started in Nigeria over three decades ago and was being conducted by some few researchers in some institutions of high learning. However, intensified research in solar with other renewable energy sources started seriously in Nigeria only towards the late 1970s; this presumably arose due to the increased awareness of the possible of renewable energy sources partly due to the so called ‘Oil-glut’ of the early seventies.

Haque (2001) carried out a study of a PVWPS with a power of 4.5 kWp, in Jordan, activating a three phases induction motor that is fixed to a centrifugal pump and a 55 m3 water storage tank. The main goal was to develop a system that could be used for techno-economic system optimization. The authors identified as performance influencing parameters: the amount of fluid extracted, frequency of distribution of irradiance and size of PV modules. For irradiance values ranging from 100 to 500 W/m^2 , volumes of 1000 to 3000 l/h of pumped water were obtained at a fixed head of 24 m. Achieving, PV array, subsystem and system efficiencies respectively of 3.27%, 39.7% and 3.76%. The techno-economic optimum system configuration is in any way the one that gives the best annual system efficiency [3].

Narale et al., (2013) explained that the development of water pumping systems for rural areas constitutes an important field of stand-alone PV systems [4]. Cuadros et al., (2004) said the key engineering alternatives used in off-grid water pumping are diesel, wind and petrol-powered water pumping systems [5].

Mahmoud (1990) stressed the widespread use of these networks to supply water for food, livestock and irrigation purposes. Characteristic of a standalone PV water pumping system is racks, water supply, storage tank and pump [6]. PV modules can also be set up on a fixed array, or on a sun racking system [7]. Since fixed PV arrays according to him are not expensive to in. Kelly et al., (2012) suggested that solar energy could be stored in two storage forms, either in water tank which can be used later at night or in a storage battery [8]. Purohit and Michealowa (2005) opined that whilst water storage tank is engaged, the storage tank will be sized to meet the load demand there is no solar irradiance at night [9]. The simplest and mainly dependable of all the system layouts for pumping purposes involves a direct connection flanked by the system and the solar array [10].When a photovoltaic system is used for irrigation purpose, the crop irrigation can now be performed by using quite a few methods such a, surface, subsurface, sprinkler and drip or micro-spray irrigation [11]. Several characteristics make drip irrigation suitable for solar powered systems. Drip irrigation is commonly used and is very efficient in pumping system, The advantage of drip irrigation is its elevated water application efficiency, which can potentially arrive at values as high as 90%, although 80% is feasible [12]. [13] Conducted his research that addressed Photovoltaic water pumping system (PVWPS) using monocrystalline and polycrystalline panels, his work shows that the average daily volume of water pumped by the two systems ranged from 3636.46 litres to 4382.55 l litres. According to him, Photovoltaic panel efficiency was 94% for monocrystalline and 65.7% for and polycrystalline systems.

3. EXPERIMENTAL WORK / METHODOLOGY

This chapter discusses the equipment, materials and mathematical model used during the research. It involves Theoretical analysis of solar water pumping, Simulations using PVSYST software, Calculation using system parameters, system efficiency, validation and collation of meteorological data for the validating area through the software. Kaduna state is located on the southern part of the high plains of Northern west Nigeria. It has geographical coordinates of Latitude 10.516N and Longitude 7.4333E. The geology is largely metamorphic rocks of a basement complex [5].

Theoretical Analysis of Solar Water pumping

To analyze the power change from solar radiation to water flow from the area of studies, the following equations were applicable.

The incident solar radiation to the PV array gives the input power

P_i to the system:

$$P_i = G \times A(W) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.11)$$

$$Where\ G = Solar\ radiation\ \left(\frac{W}{m^2}\right), and\ A = effective\ module\ cell\ area\ (m^2)$$

$The\ DC\ output\ power\ from\ the\ PVarray\ is\ given\ by$:

$$P_o = V \times I(W) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.12).$$

$$WhereV = DC. Operatingvoltage(V), I = DCoperatingcurrent\ (A)$$

Pump Motor

The pump is driven by a dc motor, this can be obtained from the expression below

Motor Power = Ph / η………………… (3.14)

Where Ph = Hydraulic power of pump [W] η = Efficiency of pump

The hydraulic power which shall be used to lift a quantity of water through a head is given by:

DOI: 10.31695/IJASRE.2023.9.9.5

$$P_h = \rho g Q H (W) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.15)$$

Where ρ = water density (kg/m3); g = specific gravity (m/s2); Q = water discharge (m3/s) and H = total pumping head (m).

System Efficiency

Array efficiency (Ea) is a function of how efficient the PV array can converts sunlight into electricity:

$$E_a = \frac{P_O}{P_I} \times 100\% \ldots\ldots\ldots\ldots\ldots.(3.16)$$

Subsystem efficiency (Es) is the efficiency of the entire system components (inverter, motor and pump):

$$E_s = \frac{P_h}{P_o} \times 100\% \ldots\ldots\ldots\ldots\ldots.(3.17)$$

Overall/System efficiency (Eo) specify how competently the overall system converts solar radiation into water delivery at a given head:

$$Eo = Ea\ x\ Es. \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.18)$$

Simulation using PVSYST SOFTWARE

PVsyst software is able to import meteo data from many different sources as well as personnel data. Diverse simulation variants, detailed losses, horizon shadings, and real components can be added to make economic evaluations. Reports can be generated after the completion of the project and information can be exported to the clipboard. The last option includes meteorological data, components, solar toolboxes, and the analysis of actual data.

The input parameters used in PVsyst software are shown in table 1-6

Table 3.1 Geographical Details

Site	Kaduna
Longitude	7.433E
Latitude	10.516N
Altitude	614m

.

Table 3.1 depicts the geographical conditions of location is to be considered. The above details are given as input to obtain the solar irradiation for site.

Table 3.2 Well characteristics

Static level depth[m]	50
Max. pumping depth[m]	105
Pump depth[m]	115
Well diameter[cm]	18

Table 3.2 gives the well characteristics of site to be considered. Static level depth of the well is taken as 50 m and well diameter is 18 cm.

Table 3.3 Storage Tank

Volume	$20m^2$
Diameter	3.4m
Height (full level)	2.2m
Feeding altitude	12m

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Table 3.3 shows the features of storage tank, which is used in water pumping system for water storage.

Table 3.4. Hydraulic Circuits	
Piping length	70m
Pipes	PE20(3/4”)
Number of elbow	1
Other friction losses	0.45

Table 3.4 depicts the features of hydraulic circuit, the above details shows number of elbow used and daily water requirements.

Table 3.5. Pump characteristics	
Model	SQF 2.-2 30-300 V
Manufacturer	Grundfos SQFlex
Pump Technology	Progressive cavity
Motor	DC Permanent Magnet
Power	900W

Table 3.5 Describes pump characteristics. The power of motor is 900 watt.

Table 3.6 PV array characteristics	
PV module	Si poly
Number of PV modules	15
Unit nominal power	80Wp
Array global nominal power	1200Wp
Max. operating power	1815Wp
I_{MPP}	58V
V_{MPP}	272V
Module area	5.6m^2

DOI: 10.31695/IJASRE.2023.9.9.5

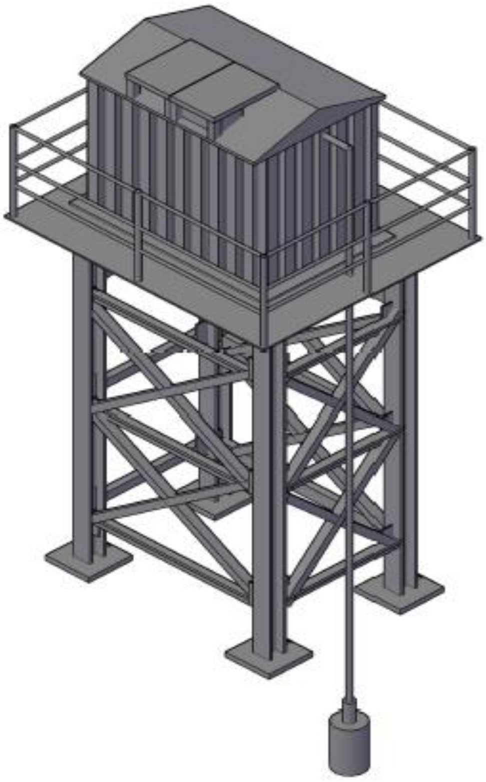
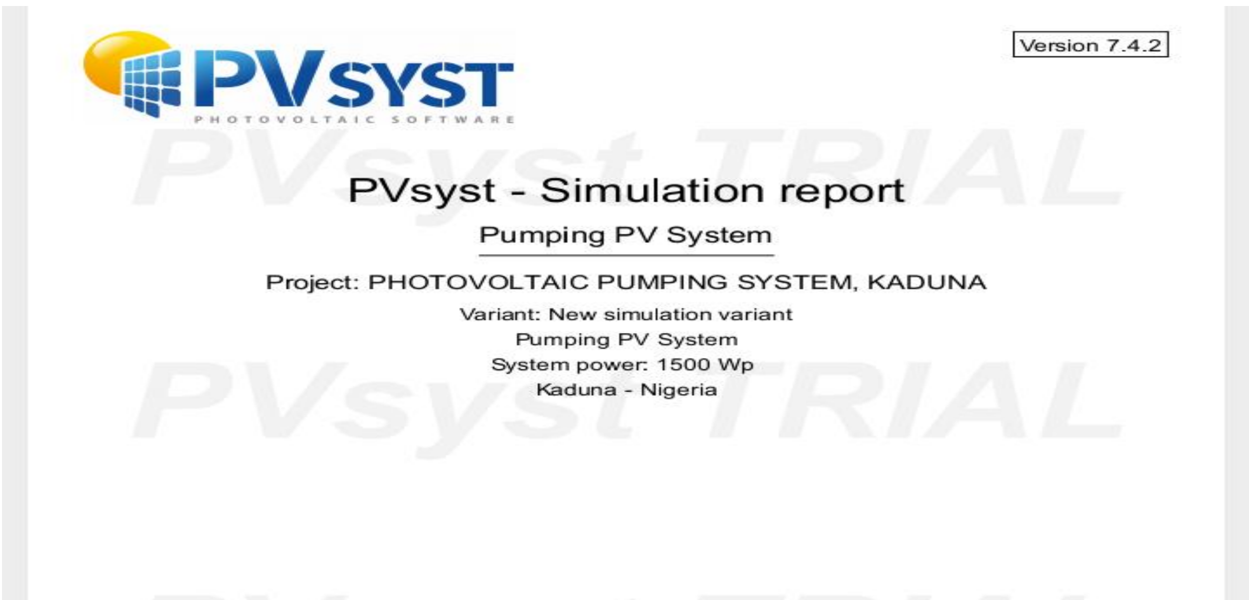


FIG 1. Validating Model

4. RESULTS

Simulations reports are depicted in Figure 2-7.


PVSYST
PHOTOVOLTAIC SOFTWARE
Version 7.4.2

PVsyst - Simulation report

Pumping PV System

Project: PHOTOVOLTAIC PUMPING SYSTEM, KADUNA

Variant: New simulation variant
Pumping PV System
System power: 1500 Wp
Kaduna - Nigeria

FIG 2: Title page

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Project: PHOTOVOLTAIC PUMPING SYSTEM, KADUNA

Variant: New simulation variant

PVsyst V7.4.2
VC0, Simulation date:
09/03/23 12:17
with v7.4.2

Project summary

Geographical Site	Situation		Project settings	
Kaduna	Latitude	10.53 °N	Albedo	0.20
Nigeria	Longitude	7.44 °E		
	Altitude	611 m		
	Time zone	UTC+1		

Meteo data
Kaduna
Meteonorm 8.1 (2010-2021), Sat=100% - Synthetic

System summary

Pumping PV System — **Deep Well to Storage**

PV Field Orientation		Water needs	
Fixed plane		Yearly Average	10.00 m³/day
Tilt/Azimuth	45 / 0 °		

System information
PV Array

Nb. of modules	6 units
Pnom total	1500 Wp

Results summary

Water		Energy		Efficiencies	
Water Pumped	3654 m³	Energy At Pump	1071 kWh	System efficiency	44.5 %
Specific	399 m³/kWp/bar	Specific	0.29 kWh/m³	Pump efficiency	57.9 %
Water needs	3650 m³	**Unused (tank full)**			
Missing Water	-0.1 %	Unused PV energy	1210 kWh		
		Unused Fraction	50.3 %		

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FIG 3: Summary of Simulation project

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Project: PHOTOVOLTAIC PUMPING SYSTEM, KADUNA

Variant: New simulation variant

PVsyst V7.4.2
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09/03/23 12:17
with v7.4.2

General parameters

Pumping PV System

System Requirements

Basic Head	62 meterW

Water needs

Yearly Average	10.00 m³/day

Deep Well to Storage

Well characteristics

Static level depth	-50 m
Specific drawdown	-0.10 m/m³/h
Diameter	18 cm
Pump level	-60 m
Lower dynamic level	-55 m

Storage tank

Volume	20.0 m³
Diameter	3.3 m
Feeding by top	
Feeding altitude	12.0 m
Height (full level)	2.4 m

Hydraulic circuit

Piping length	72 m
Pipes	PE50
Dint	64 mm
Number of elbows	2
Other friction losses	0.450

PV Field Orientation

Fixed plane

Tilt/Azimuth	45 / 0 °

PV Array and Pump

PV module

Manufacturer	Generic
Model	8.250MSGB
(Original PVsyst database)	
Unit Nom. Power	250 Wp
Number of PV modules	6 units
Nominal (STC)	1500 Wp
Modules	2 Strings x 3 In series
At operating cond. (50°C)	
Pmpp	1344 Wp
U mpp	130 V
I mpp	10 A
Total PV power	
Nominal (STC)	1.50 kWp
Total	6 modules

Pump

Manufacturer	Generic
Model	SQF 2.5-2 30-300 V
Pump Technology	Progressive cavity
	Deep well pump
Motor	DC motor, permanent magnet

Associated or Integrated converter

Type	MPPT
Voltage range	30 - 300 V

Operating conditions

	Head min.	Head Nom	Head max.	
	10.0	70.0	120.0	m
Corresp. Flowrate	3.03	2.77	2.33	m³/h
Req. power	300	900	1400	W

Control device

Model	Generic device (optimised for the system)
System Configuration	MPPT-DC converter

Water needs: monthly values

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	m³/day

FIG 4: General characterization of Well, PV array and Pump

Project: PHOTOVOLTAIC PUMPING SYSTEM, KADUNA

Variant: New simulation variant

PVsyst V7.4.2
VC0, Simulation date:
09/03/23 12:17
with v7.4.2

PV Array and Pump

Pumping system controller

System Operating Control

Generic device params adjusted acc. to the system

Power Conditioning Unit

Type	MPPT-DC converter

Operating conditions

Nominal power	1400 W
Power Threshold	14 W
Max. efficiency	96.5 %
EURO efficiency	94.5 %
Minimum MPP Voltage	30 V
Maximum MPP Voltage	300 V
Maximum Array Voltage	300 V
Maximum Input Current	7.0 A

System losses

Thermal Loss factor

Module temperature according to irradiance

Uc (const)	20.0 W/m²K
Uv (wind)	0.0 W/m²K/m/s

DC wiring losses

Global array res.	212 mΩ
Loss Fraction	1.5 % at STC

Module Quality Loss

Loss Fraction	-0.8 %

Module mismatch losses

Loss Fraction	1.0 % at MPP

Strings Mismatch loss

Loss Fraction	0.2 %

IAM loss factor

ASHRAE Param.: IAM = 1 - bo (1/cosi - 1)

bo Param.	0.05

FIG 5: Specific characterization of PV array and Pump

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Project: PHOTOVOLTAIC PUMPING SYSTEM, KADUNA

Variant: New simulation variant

PVsyst V7.4.2
VC0, Simulation date:
09/03/23 12:17
with v7.4.2

Main results

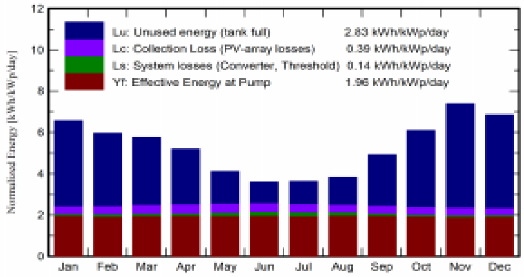
System Production

Water		Energy		Efficiencies	
Water Pumped	3654 m³	Energy At Pump	1071 kWh	System efficiency	44.5 %
Specific	399 m³/kWp/bar	Specific	0.29 kWh/m³	Pump efficiency	57.9 %
Water needs	3650 m³	**Unused (tank full)**			
Missing Water	-0.1 %	Unused PV energy	1210 kWh		
		Unused Fraction	50.3 %		

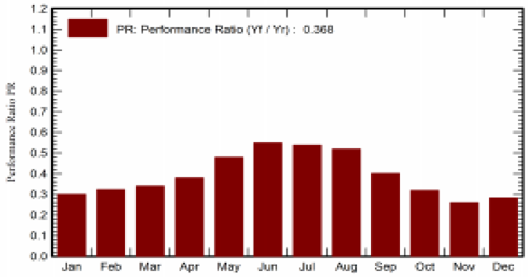
Economic evaluation

Investment		Yearly cost		Specific Cost	
Global	43.00 USD	Annuities	0.00 USD/yr	Water Cost	0.00 USD/m³
Specific	0.03 USD/Wp	Run. costs	0.00 USD/yr	Energy cost	0.00 USD/kWh

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobEff kWh/m²	EArrMPP kWh	E_PmpOp kWh	ETkFull kWh	H_Pump meterW	WPumped m³	W_Used m³	W_Miss m³
January	199.7	252.9	91.71	149.8	62.26	317.1	310.0	0.000
February	163.7	205.4	80.95	113.8	62.25	279.7	280.0	0.000
March	173.4	217.5	91.20	115.8	62.22	310.6	310.0	0.000
April	149.3	190.6	88.91	92.7	62.20	299.8	300.0	0.000
May	120.2	157.5	91.39	55.8	62.18	309.9	310.0	0.000
June	101.2	135.5	89.11	35.8	62.17	300.0	300.0	0.000
July	105.7	142.1	90.64	40.0	62.18	310.0	310.0	0.000
August	112.7	150.7	92.32	48.4	62.16	307.1	307.0	3.007
September	141.9	186.6	88.68	88.7	62.20	300.3	300.0	0.000
October	184.1	235.0	90.24	134.3	62.23	309.7	310.0	0.000
November	217.4	270.7	86.35	172.7	62.27	300.3	300.0	0.000
December	208.8	263.1	89.68	162.0	62.26	310.0	310.0	0.000
Year	1878.1	2407.5	1071.19	1209.9	62.21	3654.5	3647.0	3.007

Legends

GlobEff	Effective Global, corr. for IAM and shadings	WPumped	Water volume pumped
EArrMPP	Array virtual energy at MPP	W_Used	Water drawn by the user
E_PmpOp	Pump operating energy	W_Miss	Missing water
ETkFull	Unused energy (tank full)		
H_Pump	Average total Head at pump		

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FIG 6: Results

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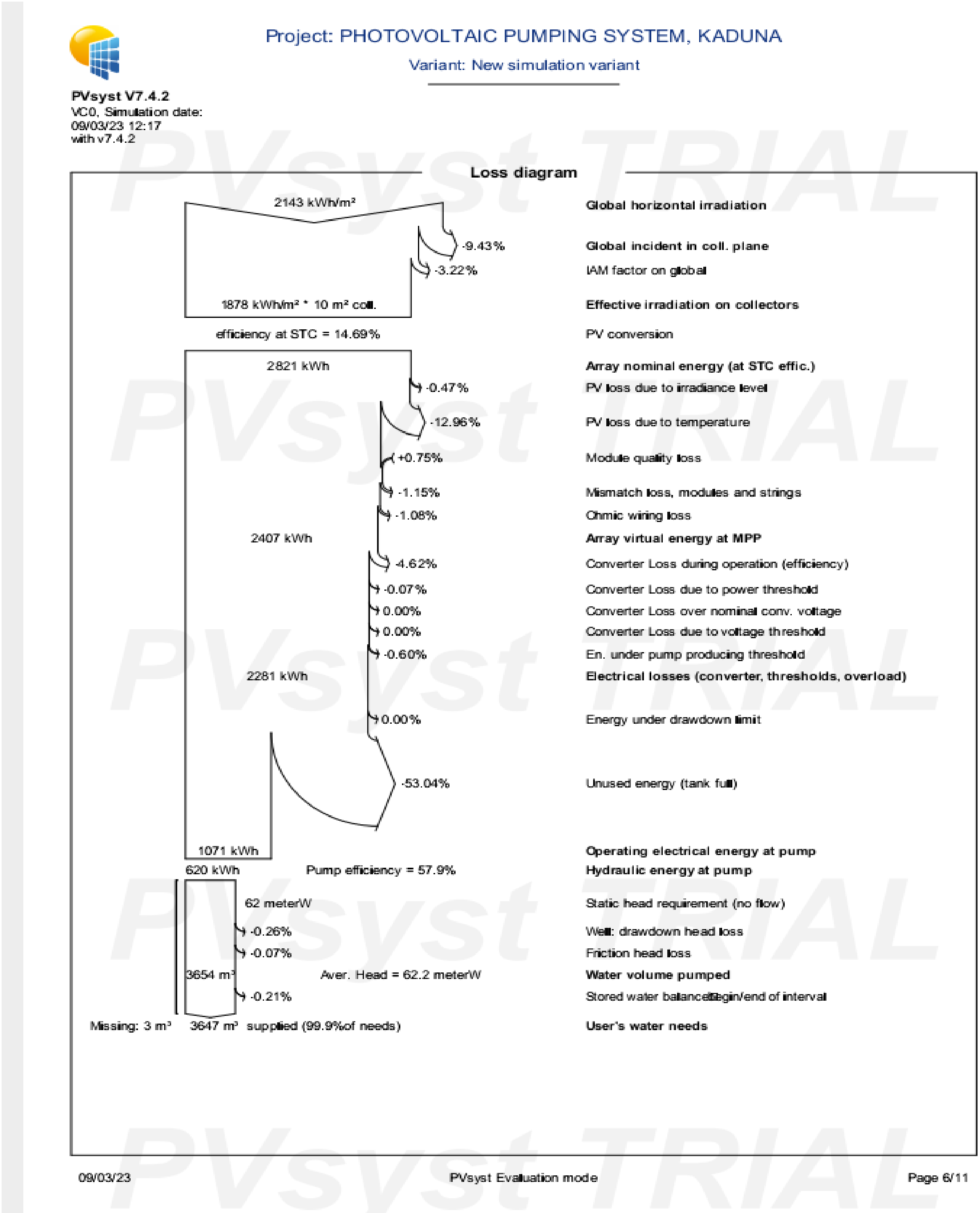

FIG 7 : System Losses

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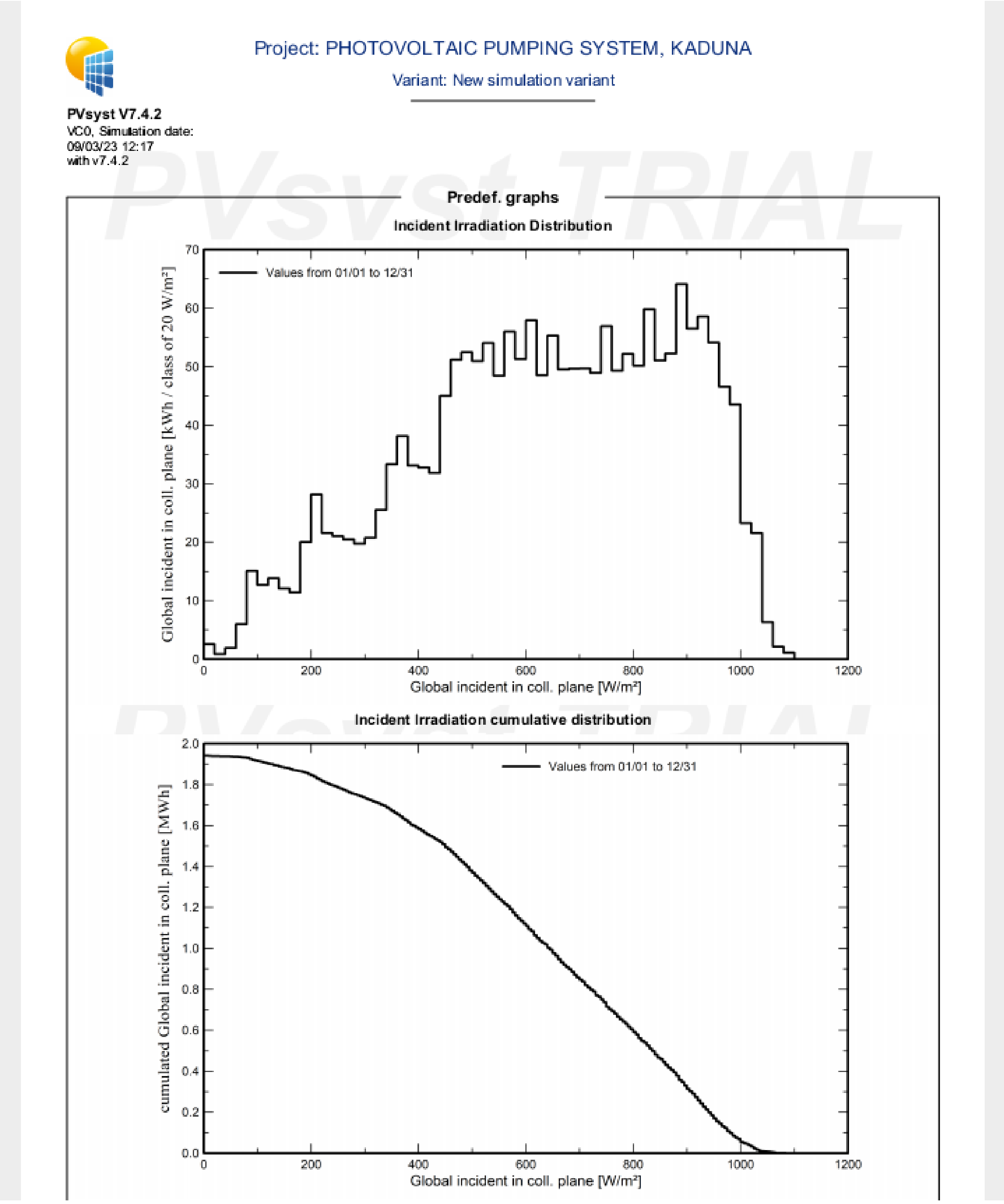

FIG 8: Incident solar radiations

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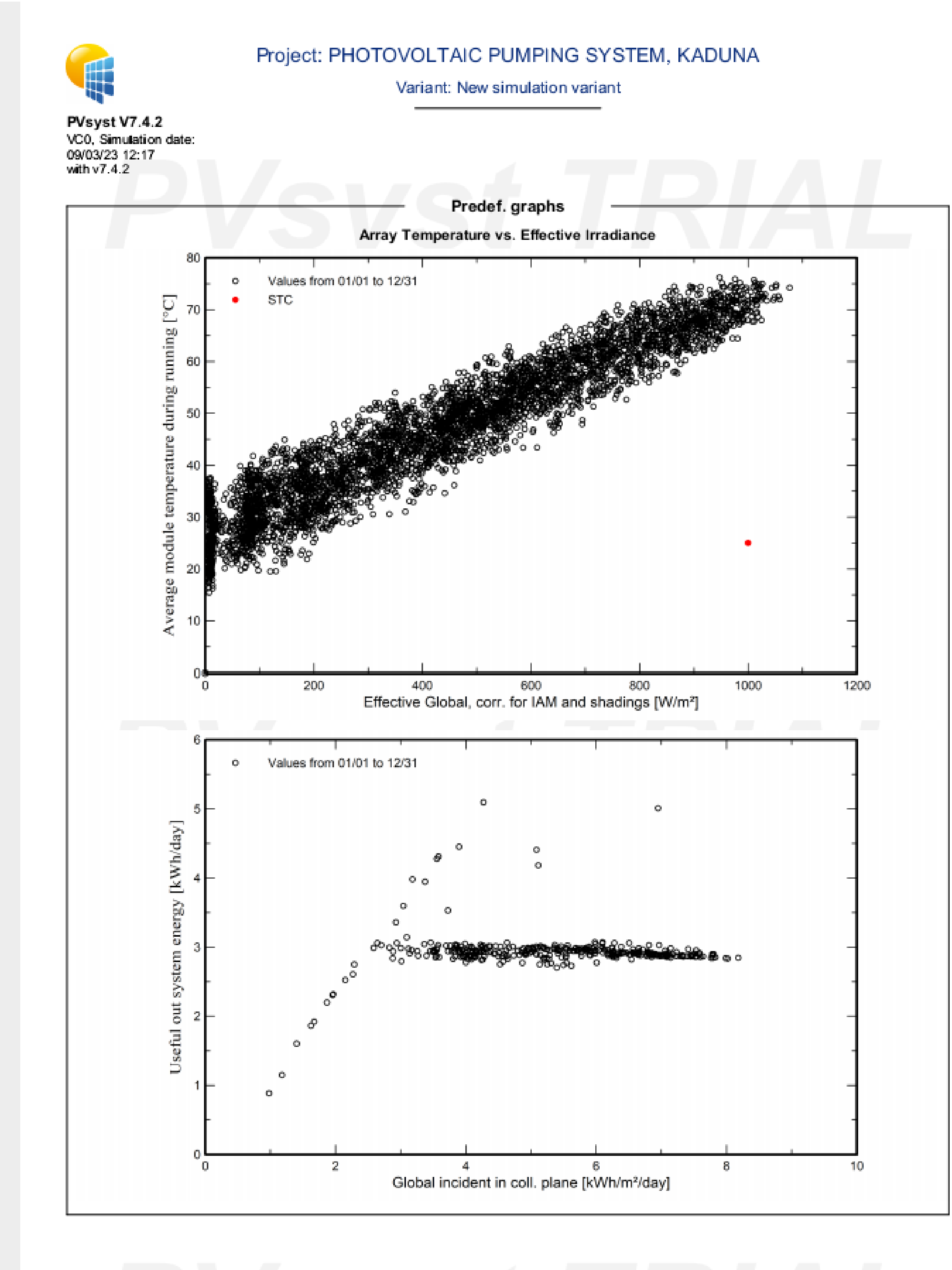

FIG 9: graph showing relationship between array temperature and effective solar irradiance

Main Results from PVSYST Simulation

System Loss Diagram

The horizontal global irradiation is 2143 kWh/m^2 as indicated in FIG 7 The effective irradiation on the collector plane is 1878 kWh/m2. Then the PV cell converts solar energy into electrical energy. After PV conversion, array nominal energy is 2821 kWh. The efficiency of PV array is 14.69% at Standard Test Condition (STC). The pump efficiency was 57.9%. Array virtual energy obtained is 2407 kWh. After the converter loss and Electrical loss, the available energy at the output is 620 kWh. The used Operating electrical energy at pump is 1071 kWh.

DOI: 10.31695/IJASRE.2023.9.9.5

System Performance PR

Figure 4 represents the performance ratio for the system. The performance ratio relates the actual yield of the PV system (Y_f) to the target yield (Y_r) and it is 0.368. This implies that the PV system was only able meet up with 36.8% of the target system.

Normalized Production per Installed kW_p

Figure 4 above represents the system's normalized production per installed kW_p. The unused energy after filling the reservoir is 2.83 kWh/kWp/day, the PV-array losses is 0.39 kWh/kWp/day, the system losses (i.e. converter, threshold losses) is 0.14 kwh/kwp/day and the effective energy at pump (i.e. useful produced energy at the MPPT output) is 1.96 kWh/kWp/day.

Fig 3.Describes the pumping system controller, Fig 2 gives the general inputs parameters.

Validation

The pump efficiency obtained theoretically was 55% while the efficiency obtained from simulations results is 57.9%. The variations in the two values maybe attributed to a mismatch of components specifications during the installations of the photovoltaic system in the validating area.

5. CONCLUSIONS

A detailed analytical investigation of a typical SWPS is studied in order to realistically estimate the solar PV sizing for the proposed installation. PVSYST 7.4.2 software is used to assess the performances of the photovoltaic pumps in the study areas.

1. The solar water pumping system is used to provide 10 m^3 water per day.

2. The simulation results have shown that the pump efficiency of the water pumping system is 57.9% and System efficiency of the water pumping system is 85.8%. The energy performance of the SWPS is satisfactory and may significantly contribute to the urban and rural water consumption needs.

3. SWPS are already widely adopted in several rural areas where the vital need for water cannot be always supported by a local electricity network and the respective PV-application

4. Thus, it is quite reasonable that SWPS may be used for covering both irrigation needs and potable water supply.

Acknowledgement:

This study was sponsored by Nigeria's Tertiary Education Trust Fund (TETFUND)

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DOI: 10.31695/IJASRE.2023.9.9.5