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Design and Simulation of Solar Powered Water Pumping System for Irrigation Purpose in Kaduna, Nigeria

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Abstract : ***Adequate irrigation of farm plants irrespective of the amount of rainfall due to seasonal variations is essential for a successful large scale farming system. In addition, the challenges of erratic electricity supply has made alternative power source for effective irrigation important. Consequently, this study designed and simulated a solar powered water pumping system for irrigation purposes. A hectare of pepper plantation was adopted as a case study in Kaduna, Nigeria. The study was carried out using a software package called PVSYST version 5.5. The result of the study predicted a pumping efficiency of 65.8%. Except for the months of April, May, June, July and August which usually fall within the rainy season and water is expected to be sufficient, the system predicted adequate water supply for pepper irrigation in other months where dearth of water is always experienced. It was concluded that: irrigation farming using solar powered water pumping system is feasible in Kaduna***.

Keywords: Solar Energy, Irrigation, Simulation, Extra-terrestrial Radiation, Evapotranspiration, Consumptive Water Use.

1.0 Introduction

Water is obviously a basic necessity to the sustenance of every life. Making it available, most especially during the dry season, both for domestic and agricultural purposes require an extra effort. Although, Kaduna has a good network of rivers, there are a lot of fertile lands which have neither rivers nor streams around them. Accessibility of water in such areas could only be achieved through a well or borehole. Hence, to enhance the sustenance of the ever growing human population, all year round cultivation, especially of perishable food crops is a necessity. However, this usually comes with a price; an accompanying increase in the cost of the products. An in-depth preliminary quest into the cause of the periodic inflation revealed that; the water pumping systems used by the farmers for irrigation are run on fossil fuels (usually diesel). Consequently, the high costs of purchase of these fuels coupled with other factors like high frequency of system maintenance contribute immensely to the increase in prices. Fortunately, during the dry season ; when water is mostly needed, Kaduna usually experiences day-long sunshine and this provides a hint into the fact that a solar powered water pumping system could be considered as an appropriate alternative.

A standalone photovoltaic (PV) water pumping system typically consists of a photovoltaic generator (i.e. a PV array), source of water, a battery and/or a water storage tank and a pump [1].Many researchers have pointed out the advantages of solar powered water pumping systems by highlighting how it can be an attractive application of renewable energy. Nadar et al. [2] analysed the technical and economic feasibility of PV water pumping systems for irrigation, concluding that the system will enhance energy security and reduce dependence on fossil fuels. They showed that the major disadvantage of the PV systems remains the high cost of the PV modules.

1.1 Modeling and Simulation

A model is a physical, mathematical, or logical representation of a system, entity, phenomenon or process [3]. Simulation is the implementation of a model over time. Simulation brings a model to life and shows how a particular object or phenomenon will behave. It is useful for testing, analysis or training where real-world systems or concepts can be represented by a model [4].

2.0 Material and Methodology

Kaduna is located on the southern part of the high plains of Northern Nigeria. It has geographical coordinates of Latitude 10.516N and Longitude 7.4333E [5]. The bedrock geology is predominantly metamorphic rocks of the Nigerian basement complex [6].The data used in the design and simulation are average minimum and maximum monthly temperatures, average monthly solar irradiation and the maximum depth among some 100 boreholes in the study area, PVSYST software version 5.5 etc.

2.1 Extra-terrestrial Radiation

The extra-terrestrial radiation (Ra) is the incident radiation outside the earth's atmosphere and it was obtained using the relation [7] as:

$$Ra = \frac{24(60)}{\pi} Gscdr[WsSin(\varphi)\, Sin(\delta) + Cos(\varphi)Cos(\delta)Sin(Ws)]$$

The latitude (φ) is positive for the northern hemisphere and negative for the southern hemisphere [7]. The conversion from degrees to radians was achieved using the relation [7, 8] as:

$$Latitude\ [radians] = \frac{\pi}{180}[decimal\ degrees]$$

2.2 The inverse relative distance earth-sun (dr) was calculated with the relation [7, 8]:

$$dr = 1 + 0.033\cos[\frac{2\pi}{365}J]$$

J= day of the year between 1 (1st January) and 365 / 366 (31st December) as the case may be.

2.3 The solar declination (δ) is the angular distance of the sun north or south of the earth's equator. It is measured in radians and obtained from the relation [7, 9] below:

$$\delta = 0.409\mathrm{Sin}[\frac{2\pi}{365}J - 1.39]$$

2.4 The sunset hour angle (Ws) is the angle for which the sun's rays are parallel to the horizon. It is given as [7, 10]:

$$Ws = \arccos[-\tan(\varphi)\tan(\delta)] = \arccos\left[\frac{sin(\varphi)\, sin(\delta)}{cos(\varphi)\, cos(\delta)}\right]$$

2.5 Evapotranspiration

Evapotranspiration (ET) is the sum of evaporation from the land surface plus transpiration and plant transpiration from the Earth's land and ocean surface to the atmosphere [11, 12]. Reference evapotranspiration (ET_0) is the evapotranspiration rate of a short green crop (grass/alfalfa), completely shading the ground, of uniform height and with adequate water status in the soil profile [12]. Alfalfa at full cover was considered as the reference plant and its evapotranspiration was obtained using the Hargreaves method expressed as [13]:

$$ET_o = 0.0023(T_{mean} + 17.8)\,(T_{max} - T_{min})^{0.5} Ra$$

Where: Tmean, Tmax, and Tmin are Average Mean, Maximum and Minimum temperatures respectively.

2.5.1 The Crop Evapotranspiration/Consumptive Water Use (ETc)

It's defined as the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions [12] and it's represented as [7]:

$$ETc = Kc \times ETo$$

Where: Kc and ETc denote crop constant and crop evapo-transpirations respectively.

With Alfalfa as the reference crop, at full cover, the Kc for pepper and tomatoes are: 0.71 and 0.66 respectively [12].The obtained daily consumptive water use by the crops are as indicated in table 4.1.

2.6 The Required Flow Rate

The required flow rate (Q) was obtained using the relation [13]:

$$Q = \frac{V}{t}\ [m^3/s]$$

2.7 The Total Dynamic Head

It is the total equivalent height that a fluid is to be pumped; taking into account, friction losses in the pipe and it is expressed by the relation [14] as:

TDH = Static Height + Static Lift + Friction Loss

2.8 The Hydraulic Power

It's the power required for lifting a volume of water through a given head and it's given as [15]:

$$P_h = \rho g Q H$$

2.9 Electrical Energy Required

This is the energy required by the motor to drive the pump. It is expressed as [16]:

$$P_e = \frac{Hydraulic\ Energy}{Subsystem\ efficiency} = \frac{Ph}{\eta}$$

$\eta = \eta$converter (0.95) x η motor (0.7) x ηpump (0.6) x ηpiping (0.90) [16]

2.10 Size of the Solar PV generator

The size of the PV generator is estimated from the expression [1] as:

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$$\text{PV Wattage} = \frac{\text{Electrical Energy requirement}}{\text{PV Energy loss x Sunshine hour}}$$

2.11 Selection of System Components

Based on the plant consumptive water use and the system parameters, the following points were noted before adopting some properties of the simulated system.

(a)The well depth was chosen to accommodate the deepest among the 100 wells whose data were obtained in the study area.

(b)The storage tank was sized to accommodate the highest consumptive water use which is 43.51$m^3ha^{-1}day^{-1.}$Also the feeding altitude was chosen because the irrigation system adopted (drip irrigation), which is the most suitable for solar water pumping system [19] is a low pressure system of irrigation.

(c)Grundfos SQFlex D.C pump was adopted because of economy, market availability, durability and the fact that it comes with a MPPT system among others [20].**2.12 Simulation using PVSYST Software**

PVSYST software is a PC software package for the study, sizing and data analysis of complete PV systems. It is able to import meteorological data from different sources and also accept data manually. The software consist of three main design options [17]: The second aspect is the project design option; which allows the complete study and analysis of a full-featured model of pumping systems with accurate system yields computed using detailed hourly simulation data was the one employed in this research work.

3.0 Results and Tables

Table 4.1: Crop Consumptive Water Use

Month	$m^3ha^{-1}day^{-1}$	$mmday^{-1}$	$Inchday^{-1}$
January	33.92	3.392	0.14
February	39.60	3.960	0.16
March	43.51	4.351	0.17
April	43.07	4.307	0.17
May	37.68	3.768	0.15
June	33.15	3.315	0.13
July	30.20	3.020	0.12
August	30.25	3.025	0.12
September	33.02	3.302	0.13
October	35.06	3.506	0.14
November	36.33	3.633	0.14
December	35.40	3.540	0.14

Table 4.2: Balances and Main Result From PVSYST Simulation

	GlobEff	EArrMPP	E PmpOp	ETkFull	H Pump	WPumped	W Used	W Miss
	kWh/m²	kWh	kWh	kWh	meterW	m³/day	m³/day	m³/day
January	214.8	192.5	134.0	48.67	29.11	34.45	33.92	0.000
February	195.6	173.0	139.1	24.86	29.18	39.55	39.60	0.000
March	208.7	186.3	168.6	7.95	28.94	43.35	43.51	0.000
April	159.9	144.5	136.9	0.00	26.21	37.31	38.09	4.984
May	145.0	132.0	125.0	0.00	24.73	33.54	33.66	4.016
June	124.1	113.2	104.6	1.91	23.71	29.41	29.37	3.777
July	118.2	108.8	102.9	0.00	22.86	28.51	28.33	1.870
August	115.2	105.7	99.6	0.00	23.01	27.54	27.25	3.000
September	142.4	130.3	119.8	3.80	25.00	33.06	32.85	0.175
October	179.5	163.7	132.2	23.31	27.10	34.56	35.06	0.000
November	203.3	181.9	139.0	34.00	28.78	37.11	36.33	0.000
December	215.1	193.7	137.8	46.60	29.01	35.50	35.40	0.000
Year	2021.9	1825.7	1539.7	191.09	26.31	34.45	34.41	1.489

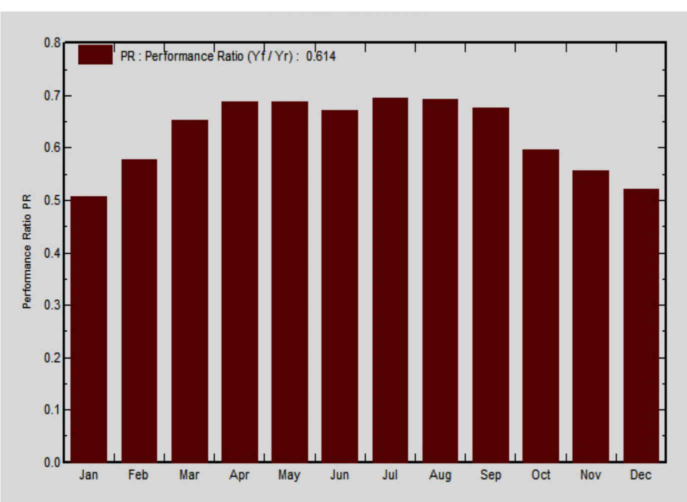

Figure 4.0 System Performance Ratio

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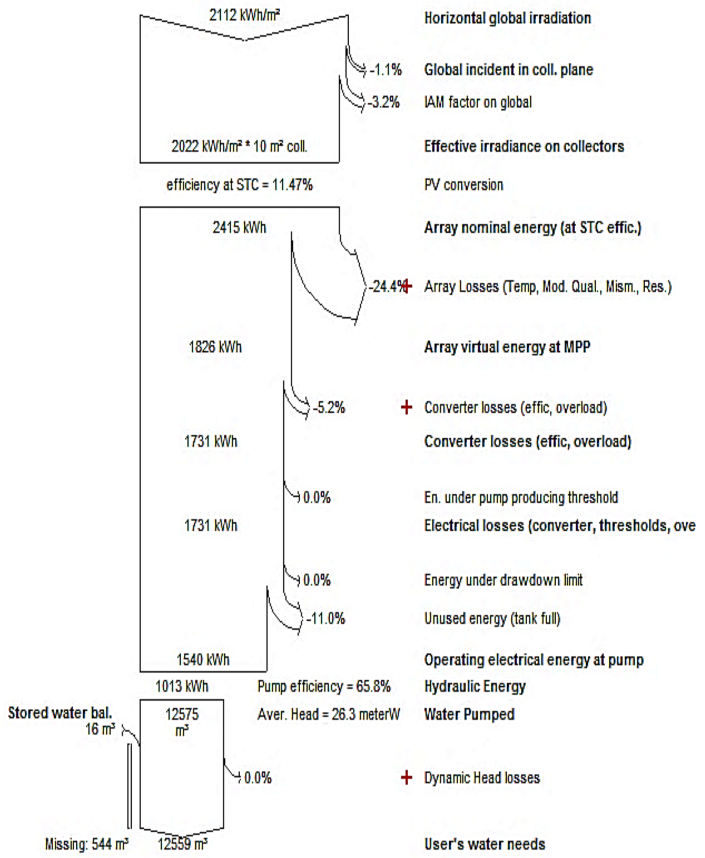

Figure 4.1 System Loss Diagram

3.1 Discussion

This section discusses the results obtained from the research work.

3.2 Crop Consumptive Water Use

The implication of the obtained value of crop consumptive water use is that: for the month of January in Kaduna, a drip irrigated hectare of pepper plantation with rows at every 4 feet (common spacing between drip irrigation emitters) will need 34.2m^3 of water per day. This explanation also applies to the remaining months of the year as the respective values are indicated in table 4.1

3.3 Balances and Main Results from PVSYST Simulation

Table 4.2 depicts the balance and main results of PV based water pumping system considering pepper evapotranspiration at full cover. Yearly global effective irradiation is 2021.9kwh/m^2. The yearly Array virtual energy at Maximum Power Point (MPP) is 1825.7kwh.The total energy used by pump throughout the year is 1539.7kwh..Yearly average head at pump is 26.31m. From the months of October to March, the system provided all the water needed. In the month of September, there was water miss (loss) of 0.175m^3 and this amounted to 0.53% water insufficiency for the month. For the month of April, May, June, July and August, daily water losses were 4.984, 4.016, 3.777, 1.87 and 1.87m^3 respectively and these imply 11.6, 10.7, 11.4, 6.19 and 9.91% water insufficiencies. Since the water losses were mostly recorded during the rainy season, this imply that; if the system were to provide the plant water needs during the period, such water insufficiencies would be recorded because the PV generator will receive less sunlight due to the cloudy nature of the atmosphere. However, because nature provides the plant water needs during this season, the pumped water could be utilized for domestic or other applications.

3.4 System Performance PR

Figure 4.0 represents the performance ratio for the system. The performance ratio relates the actual yield of the PV system (Yf) to the target yield (Yr) [1] and it is 0.614 for the simulated system.

3.5 System Loss Diagram

Figure 4.1 represents the overall loss diagram for the system. The horizontal global irradiation is 2112kwh/m^2.The effective irradiation on the collector plane is 2022kwh/m^2. Haven received the energy from the sun; the PV converts it into electrical energy. Subsequent upon conversion, the PV array nominal energy is 2415kwh.The PV array efficiency is 11.47% at Standard Test Condition (STC).Due to array losses, array virtual energy at Maximum Power Point (MPP) is 1826kwh.After converter and electrical losses, the available energy at the output is 1540kwh.The pump efficiency is 65.8%.The total water pumped is 12559m^3 while the total water loss is 544m^3.

4.0 Conclusion

From the results and the foregoing discussions, the following conclusions were arrived at:

The simulation predicted a pump efficiency 65.8% which in close agreement with previous works [1].The system also predicted all the water needed for irrigation during the dry seasons and this is a suggestion that; for irrigation purpose, the system could work effectively even without batteries. Also during the rainy seasons, when water is abundantly available, the water pumped by the system could be used for other purposes apart from agriculture. This will enhance a cleaner environment and facilitate access to cleaner water in the rural areas. It is therefore recommended that the system should be physically built without scaling down, tested and compared to the simulated model.

Also, to facilitate farmers' access to the lots of benefits of the solar powered pumping system, the government should come to the aid of farmers by providing loans and other services to ease the system implementation. In the event of this, year round cultivation will be encouraged and life will be easier for the common man through a drastic reduction in the price of agricultural commodities.

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