Design and Performance Analysis of an Oil Pump Powered by Solar for a Remote Site in Nigeria

Onyinyechukwu Chidolue and M. Tariq Iqbal

***Abstract* — Oil companies typically abandon stripper wells with production rates below 15 barrels per day because the production and maintenance cost exceed the pumping rate. Oil spillage is the primary cause of low production rates; an example of such failure is the Oloibiri oil well in Nigeria. During the peak of operation, the flow rate was 5,100 barrels per day in 1960 and was abandoned due to the declining production rate. The Oloibiri oil site has 18 drilled wells, and only the oil well 17 can be classified as stripper well. Because Nigeria has high solar irradiance and insolation, a proper PV system sizing for a solar-powered pump that should lift oil from a depth of 3800 metres at a flow rate of 15 barrels per day is evaluated for two different running times. In that way, the solar-powered pump will be used to solve the ongoing issue of stripper oil wells by curbing oil spillage from the oil wells abandoned by these production companies and rendering a low-cost pumping system. This paper evaluates the pump performance and completes the system design. It compares the system design to the PVsyst and HOMER sizing.**

***Keywords* — HOMERPro, Oil Pumping, Photovoltaic, PVsyst, Remote Oil Well, Solar Energy.**

I. Introduction

More than 3.2 million abandoned oil and gas wells in the United States are obsolete for various reasons. The effects of stripper wells are environmental concerns caused by oil spillage. Stripper wells produce fewer than 15 barrels of oil per day; according to Energy Information Administration (EIA), 380,000 remote oil wells in the US are in terrible condition and pollute the environment [1]. Oil spillage affects agriculture, climate change, and aquatic life. These numerous abandoned oil wells are still actively polluting the environment, and the spill hazard is still a concern. Other cost-effective options, like renewable energy, should be incorporated to power the pumping system. Two hundred eighty-one kilotons of methane have been released into the atmosphere in the US from abandoned wells [2],[3]. Methane is the most dangerous compared to other greenhouse gases that trap oxygen.

II. Literature Review

Five wells are operating in the Aztec Willson K property [4]. However, there is no power supply because of the remote setting, and each well was expected to produce just five barrels per day; as a result, the project's costs needed to be kept at a satisfactory rate due to the low pumping rate. The site's location makes installing electricity lines expensive because of the lack of infrastructure to build a power grid. A submersible progressive cavity pump was installed because of its capacity to use solar power and lower installation and maintenance costs, and the DC brushless motor was selected for the pumps' low power requirements, which is compatible with the PV system. The PV system design and a total remote monitoring capacity are installed because the site location is remote; cloud-based software is used for system monitoring. All pumps are monitored and managed by the software using any internet-connected device. A liquid level sensor monitors the fluid level in each well and sends the data via the cellular network.

In [5], the project aims to support the company's target to reduce its carbon emissions across the Cooper Basin and Queensland in Australia by 5% by 2025 and the Energy Solutions team is created to drive the increment of energy efficiency and the reduction of carbon emissions. It believes that switching the power source from crude oil to 100% renewable energy will positively affect the environment and the economy by increasing system uptime and production, reducing fuel usage, and removing dependence on fuel generators, which are not always dependable. Additionally, it will reduce maintenance and fuel trucking operational costs. High-efficiency photovoltaic (PV) arrays are used in the system, and the DC power generated is converted to AC electricity by an inverter to power the beam pump. Excess energy is stored in the battery. When the load on the beam pump exceeds the capacity of the PV generation, the batteries release the stored energy through the inverters to power the pump. A control system monitors and controls the charging and discharging of the batteries remotely.

The solar-powered oil pumping system product built by Solar Lighting International consists of a Crank Rod Pump for shallow and low-flow oil wells, especially those located in rural areas [6]. Unlike the linear rod pump, the solar-powered crank rod system eliminates the technical mechanics of conventional pumping equipment. It transforms variable-speed rotary motion into vertically reciprocating motion, which powers the rod string using a primary crank mechanism. The unit is small, light, and simple to install and move. It mounts directly to the wellhead. The crank rod pump speed is low, allowing low-volume wells to continue producing without being shut down, making it a perfect alternative for pumping stripper wells. The sucker-rod pump has a control system that maximizes production while

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protecting the pumping system. The crank rod pump system's unique ability to operate on solar power makes it a flexible and environmentally responsible solution for regions disconnected from the power grid. Power demand is balanced by flywheel energy storage, while power usage control ensures that the complete output of the solar collecting array is always used, allowing the device to pump in a wide variety of fluids. Only a few solar-powered oil pump studies are found in the literature review, and none of the current studies provided full design details and methods used. In this paper, we present a case study for a site in Nigeria and include a complete design, system sizing and analysis of the designed system.

III. Site Characteristics: Oloibiri Oil Field

The Oloibiri oilfield is located in Bayelsa State, Nigeria, and the 13.75 km^2 oil site is under a marsh of Oil Mining License OML 29. The discovery well Oilwell 1 depth is 108 feet and was founded on August 3, 1955 [7]. On average, the field produced five thousand hundred barrels daily for the first year. After that, production increased as new wells were drilled and put into use, reaching peak production in 1964, with a total of eighteen oil-producing wells. The field produces heavy oil with an API rating of 20.6, with the oilfield's total production rate of over 20 million barrels during its 20-year life. When oil production finally ended in 1978, the field was shut down the following year due to the low production rate, which was not profitable for the companies [7]. The Oloibiri oilfield was neglected without any possibility of recovering the remnant still present on the site. The pipeline connecting the Oloibiri field to Port Harcourt and the Bonny was constructed by Royal Dutch Shell, the country's first crude oil pipeline. The first crude oil exports from Nigeria's Oloibiri oil field occurred in February 1958, initially at a rate of 5,100 barrels per day.

A. *Oil Well Development*

After declining production, the Oloibiri-17 appraisal well was drilled to a depth of 12,520 feet, and this was due to the pump rate from the previous appraisals being drastically low. The oil spillage from Oloibiri caused most oil wells to dry up. At that time, the field's output decreased less than its peak production period. Only oil well 17 was considered a stripper well with a production rate of under 15 barrels per day [7]. The current condition of the oil well and oil spillage are shown in Fig. 1 and Fig. 2.

Fig.1.Oil Well 17 Current State [8].

Fig. 2. Oloibiri Oil well spillage.

Since oil well No. 17 is considered a stripper well with a production rate of about 15 barrels per day, this paper will design and analyze a solar power pump.

IV. Issues of Abandoned Oil Wells in Nigeria

The House of Representatives Petroleum Resources (Upstream) and Environment Committees looked into the precise reason behind the oil spills at the OML 63, OML 18, and OML 29 neglected wells in Nigeria. Cawthorne Channel Well 15 under the Oil Mining Lease (OML) 18 is a deserted and remote well which was the cause of the oil spill [9]. According to reports, hundreds of thousands of barrels of crude oil were dumped into the Santa Barbara River, and the spillage ruined the ecosystems that sustain farming, drinking water and aqua life. Unfortunately, the root cause of the oil leak on OML 29 is still unknown. OML 63 experienced a leak, the cause of which has not yet been determined and is under review [10]. In Nigeria, over 800,000 barrels of crude oil are still being produced at a lower rate than before. Although the exact reason for the Nigerian oil well leak is unknown at this time, it is believed to be the result of low-quality oil construction or piping material wear and tear.

V. Solar Energy in Nigeria

The geographic location of Nigeria is an advantage for solar energy utilization due to its high solar irradiance. Solar energy in Nigeria has a high global horizontal irradiance, with the northern part receiving the highest portion. The country has a solar radiation value of roughly 19.8 MJ/m^2 and 6 hours of sunshine on average per day. The amount of sunshine varies depending on the site location ranging from 9 hours in the far north to 3.5 hours near the coast [11], [12].

Nigeria typically receives about 7.00kWh/m^2, which is 25.2MJ/m^2 of solar radiation daily. Fig. 3 shows the solar radiation map of Nigeria and can be used to estimate the nation's solar capacity, which is between 3.5 kW/m^2/day to 7.0 kW/m^2/day, with average daily sunshine hours of 4 to 7 [11]. There are currently only a few recent developments in remote microgrid systems using solar energy for other applications rather than residential use.

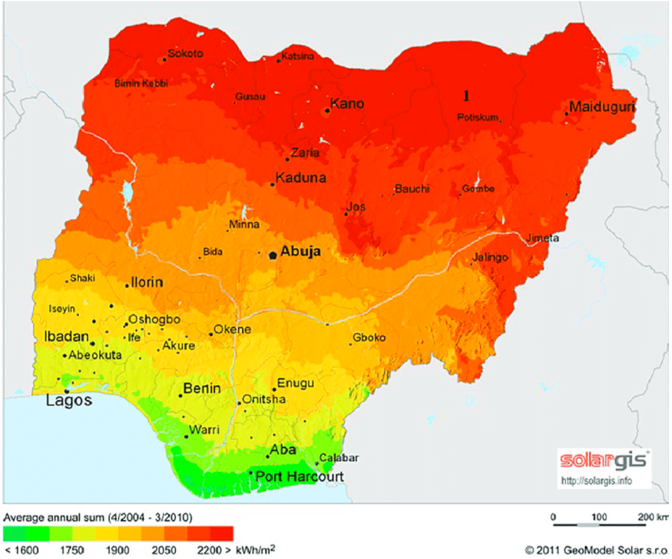


Fig. 3. The geographical Solar irradiance range in Nigeria [11].

VI. System Design Calculation

The primary aim of this design is to evaluate the best-fit running time for the solar pump, and this will be compared under two conditions, first, when the system runs at the solar isolation of the location, that is 5 hours a day and then when the system runs for 24 hours non-stop. The pump performances for each condition are carried out on Pvsyst software since the site characteristics, and oil well parameters can be inputted in the software, while the PV system sizing will be carried out using HOMERpro.

A. Site Description

The choice of a pump depends on the flow rate and head. The pumping level was chosen at 3800 m to avoid pump damage from any foreign body, like sediments or sand from crude oil. The oil well depth is 3816 m with a total dynamic head of about 3820 m and a static water level to the ground of 3710 m. About 15 barrels of oil are produced at this location each day, which is equal to $2.4m^3/day$ per day. Under the following running time, the performance of the two systems will be compared and examined.

- Condition A; the system runs for 5 hours daily when it is sunny in the vicinity.

$$Flow\ rate\ per\ second = \frac{2.4}{5\times60\times60} = 0.00013m^3/s\ (0.5\ m^3/h) \quad (1)$$

- Condition B; system is running for 24 hours, non-stop, irrespective of solar irradiance.

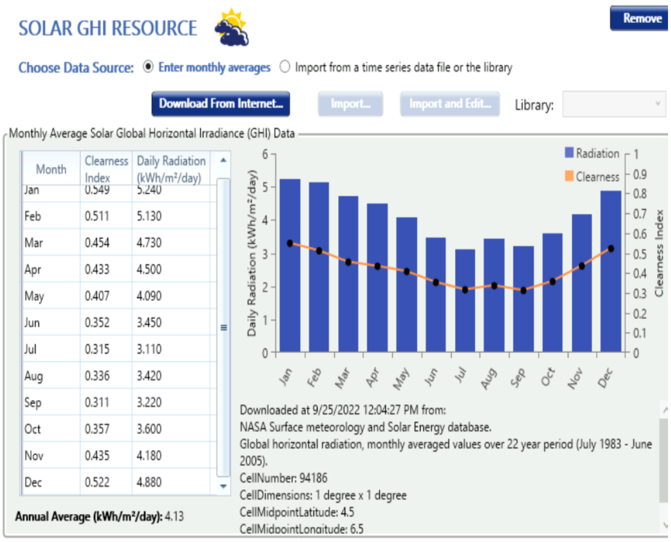
$$Flow\ rate\ per\ second = \frac{2.4}{24\times60\times60} = 0.000027m^3/s\ (0.1\ m^3/h) \quad (2)$$

$$TDH = 3816 + [(0.9\ 1) + 5\,] \times 0.2 = 3817\,m \quad (3)$$

but 3820 m will be the estimation for the total dynamic head to give room for other losses.

B. Solar Irradiance of the Site

The best use for this renewable energy technology in Nigeria will be the integration of solar energy due to the country's high solar irradiance and prolonged hours of solar insolation. The solar irradiance of the site was evaluated using the Homer software. Fig. 4 below indicates the site's solar resources obtained from HOMERpro software.



Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.549	5.240
Feb	0.511	5.130
Mar	0.454	4.730
Apr	0.433	4.500
May	0.407	4.090
Jun	0.352	3.450
Jul	0.315	3.110
Aug	0.336	3.420
Sep	0.311	3.220
Oct	0.357	3.600
Nov	0.435	4.180
Dec	0.522	4.880

Annual Average (kWh/m²/day): 4.13

Fig. 4.The solar average global horizontal irradiance data for the site from homer.

The highest monthly average solar irradiation occurs in January, while the lowest occurs in July. Oloibiri, Nigeria experiences an annual average solar radiation of 4.13kWh/m^2/day. The solar day was demonstrated by the minimum and maximum sunshine durations varying from 5 to 9 hours.

C. Pump Sizing

The proper pump sizing can be calculated using hydraulic power over the efficiency for a simple calculation.

$$hydraulic\ power\ =.\rho \times g \times H \times Q \quad (4)$$

$$Shaft\ power\ = \frac{hydraulic\ power}{efficiency} \quad (5)$$

where,
ρ is the density.
H is the total dynamic head in m,
Q is the flow rate in m^3/s, and
g is the gravitational constant in m/s^2.

A pump efficiency of 30% is assumed for the simple calculations to give a rough sketch of the system design. Heavy crude oil density is 925 kg/m^3. However, because of the well's depth and high pressure at the bottom level, the density is nearly equal to that of water which is 1000 kg/m^3. Since the oil will be hot at that depth, its viscosity is low.

- As previously demonstrated, the total head dynamic for condition A, or a system operating for 5 hours per day, is 3820 m, with a maximum flow rate of 0.00013 m^3/s. Based on the hand calculation efficiency assumption, the calculated hydraulic power is 4,506 W, and the shaft power of 15 kW can deliver the necessary amount of oil.

- For condition B, a system that operates continuously with a maximum flow rate of just 0.000027 m^3/s, the calculated hydraulic is 934.96 W, and the shaft power of 3.11 kW can, according to the hand calculation, deliver the necessary amount of oil at a 30% efficiency.

The above calculation provided a rough idea of the system design; however, comprehensive system sizing is carried out using solar energy software.

VII. Solar Pump Design by Pvsyst

PVsyst software is used to properly size the solar pump to fit the system needed for the site's characteristics and provides specific parameters that describe the oil well, like lower dynamic level pump level, borehole diameter, static level and drawdown. Because of the well's depth, the density of the oil is equal to that of water. The following oil well specification is required for the system design in Fig. 5. The medium-pressure seamless steel material with an inner diameter of 200 mm and an outer diameter of 217 mm is used as the customized delivery pipe material.

A. Pump Sizing for a Running Time of 5 hours/day

With a minimum head of 3702.7 metres of oil and a maximum head of 3712.7 metres, as shown in Fig. 6, PVsyst indicated the hydraulic power is 4850W and suggested pump power of 18.2 kW and PV system of 23 kWp.

B. Pump Sizing for Continuous Running Time (Non-Stop)

The PVsyst software suggested nearly the same pump size as the other running conditions. The flow of 0.000027 m^3/s was entered as shown in Fig. 5, suggesting the pump power as 18.5 kW, a PV power of 18.5 kW, and tank storage of 9.6 m^3 to meet the load demand when operating 24/7, as shown in Fig. 7.

VIII. PV Sizing by HOMERPro Software

Given that PVsyst recommends sizing at about 18.2 kW and 18.5 kW for the two conditions, respectively, 1.8 kW is added to account for additional energy requirements for the system monitoring and extra lighting. To precisely determine the ideal PV rating to handle the system's required electrical load for a 5-hour daily and continuous flow operating period will be optimally done using HOMERPro software; this is one limitation of PVsyst.

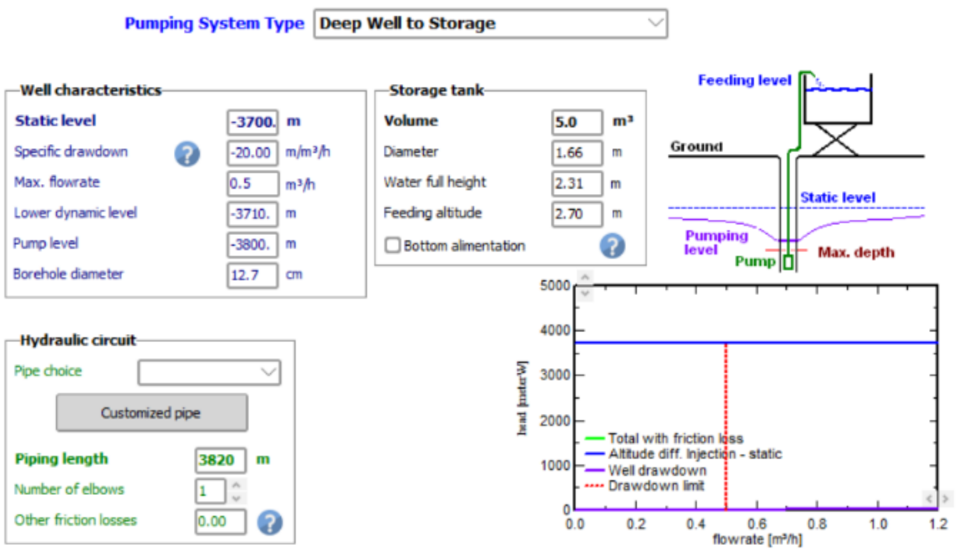


Fig. 5. The oil well characteristics inserted in PVsyst software.

Fig. 6.The pre-sizing suggestion done by Pvsyst for 5 hours running time.

Fig.7. The pre-sizing suggestion done by PVsyst for a non-stop running time.

Fig. 8. Load profile when the system runs for 5 hours/day.

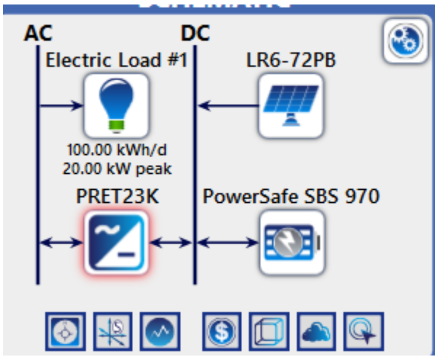


Fig. 9. System Sizing Architecture.

The system is intended to be used during its operating window of 11 am to 4 pm when solar irradiance is at its highest. Fig. 8 and Fig. 9 show the system design and load profile for 5 hours of running time in HOMERpro.

For the system design, a 22.3 kW converter, a 50 kW of 370W 24V Solar panel, 40 (970Ah, 12V) batteries, and One string of 20 batteries has a DC bus voltage of 240V is used. Fig. 10 shows the renewable fraction of 100%, 33.9% of the electricity being in excess, 0.08% of the load being unmet, and 0.09% of the capacity shortage.

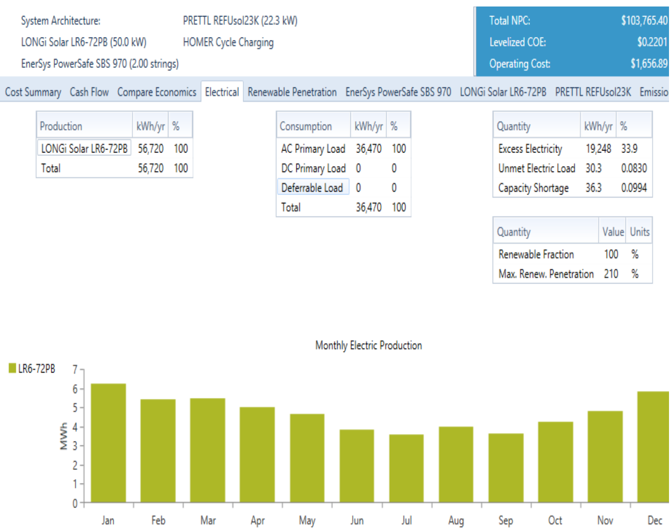


Fig. 10. The simulation result details for the 5 hours running time system

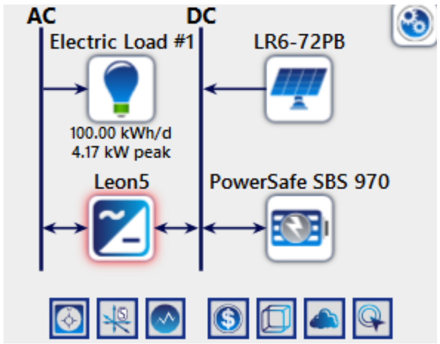


Fig. 11. System Sizing Architecture.

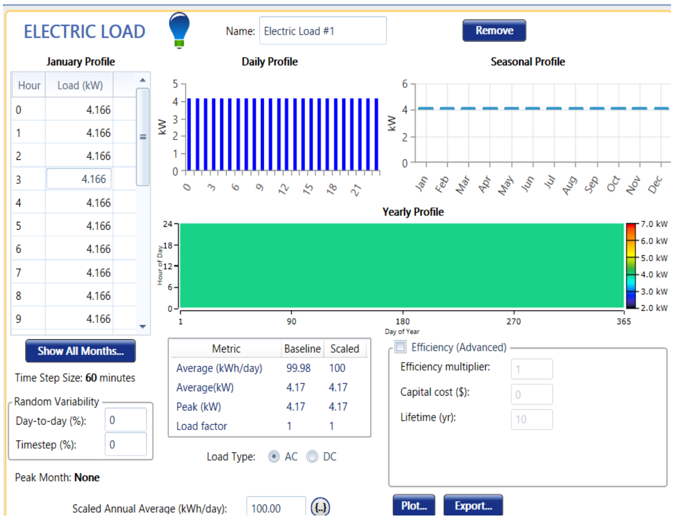


Fig.12. Load profile when the system runs for the non-stop running time.

PV sizing for the system that operates continuously under the same sizing architecture as under condition A. The system design includes a 5.88 kW converter, 40 (970 Ah, 12 V) batteries, and 54.9 kW of 370W, 24 V Solar panels. Fig. 13 depicts a 100% renewable percentage, with 38% of electricity being in excess, 0.8% of the electric load being unmet, and 0.09% of capacity being short. The 240 V DC bus voltage, or twenty 12 V battery banks connected in series, was set.

The system's 24-hour operation results in a higher PV capacity and surplus electricity compared to condition A.

Fig. 13. The simulation result details for the non -stop running time system.

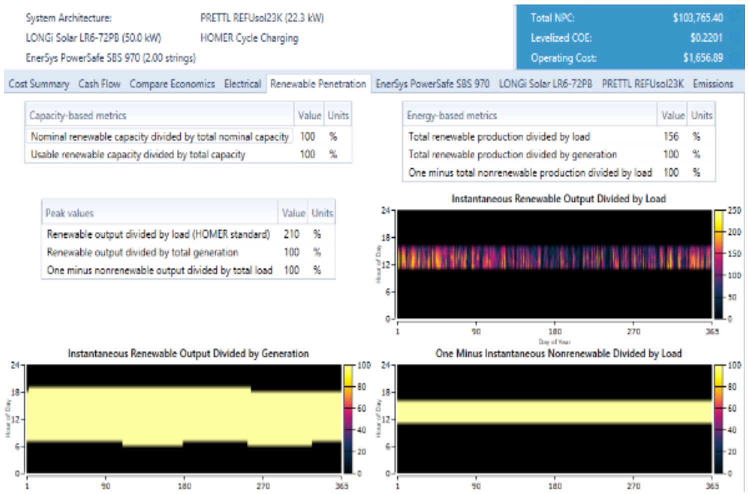


Fig. 14. The renewable penetration for on the PV panel for the 5 hours running time.

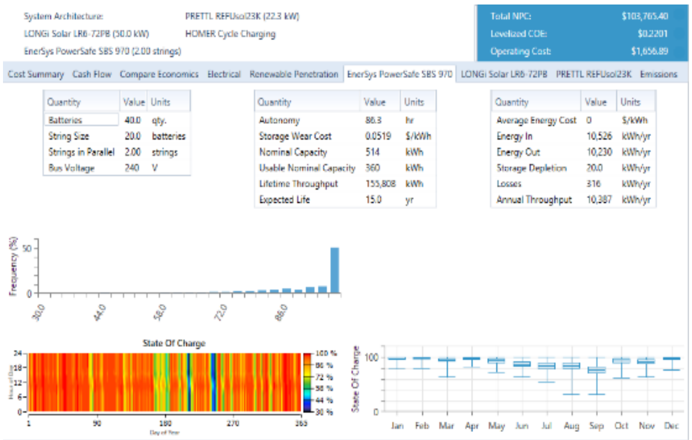


Fig.15. The battery performance details for the 5 hours running time.

Fig.16. The battery performance details for the non-stop running time.

A. PV Panel and Battery Performance

The penetration level met all load requirements by 156%, as shown in Fig. 14. However, the battery's internal system characteristics reveal that the state of charge began to decrease significantly in August.

Fig. 15 shows that in September, this reduction ended for a system running for 5 hours. Even though the specifics of renewable penetration are the same in both situations, the battery's internal system characteristics demonstrate that the state of charge rapidly depletes in August. Fig. 16 shows that in September, this decline came to an end.

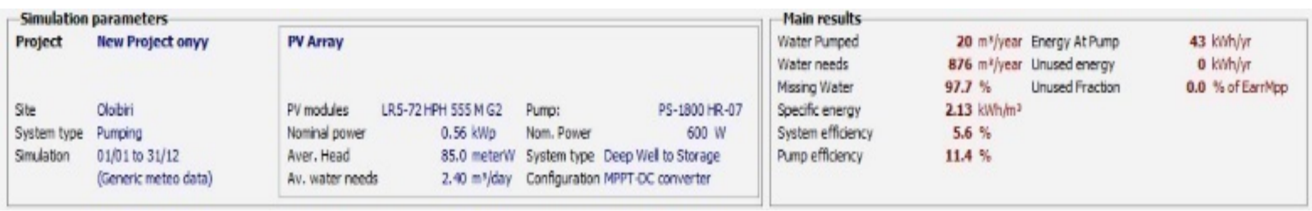


Fig. 17. The simulation parameters and results for the 5 hours/day running time.

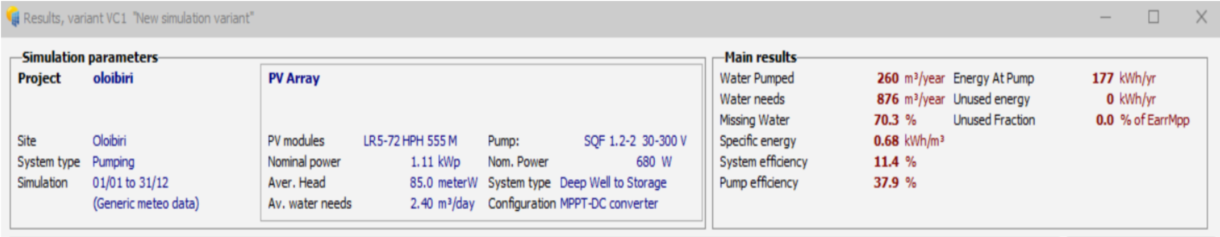


Fig. 18. The simulation parameters and results for the non-stop running time.

IX. System Performance

The oil well is too deep for PVsyst to evaluate the pump dynamics. As a result, the maximum head is set at 100 metres, and the static head and dynamic level are set at the same level position as the site characteristics.

In order to account for the TDH of 3820 m, each result will be multiplied by 38.2 to mimic the system's performance fully. The pump is specified based on the requirements of the static head and the pump power.

For the system evaluation for condition A, a 1.4 kW Grundfos Solflex DC pump with a brushless DC motor with a maximum power of 1400 W, 120 V, and 3.8 A is used. The pump power for condition A is 422 W by PVsyst. Main result of Fig. 17 demonstrates that the pump performance efficiency is 37.9%, and the overall system efficiency is 11.4%.

For condition B, the pump power is 328 W. Lorentz DC pump with a brushless DC motor with a maximum power of 600 W, 140 V, and 3.1 A is used for system evaluation. Fig. 18 indicates that the pump efficiency is 11.4%, overall efficiency is 5.6%, and there is 97.7% missing oil.

Fig. 17 represents a system size for a 100 m depth along with the flow rate for a 5-hour running time. Recall that every result will be multiplied by 38.2. Therefore the PV power is 20.36 kWp, and the pump power is 16.12 kW, with losses not considered.

Fig. 18 represents a system size for a 100 m depth along with a continuous flow. Recall that every result will be multiplied by 38.2 in Fig. 18. Therefore the PV power is 15.9 kWp, and the pump power is 12.5 kW with losses not taken into account.

According to the above design and analysis, the design sizing for both systems is the same, but the system's efficiency when running for five hours is best suited for the location. The system consists of a 22.3kW converter, 40 (970Ah, 12V) batteries, and a 50 kW of 370W 24V Solar panel. Fig. 19 offers a thorough system design diagram that will run for five hours.

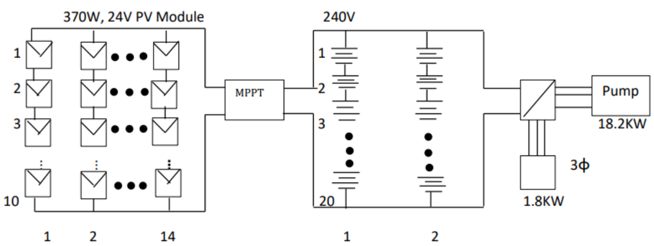


Fig. 19. Detailed System Design Diagram.

X. Conclusion

The environmental effects of an abandoned well with a low production rate are catastrophic. Alternative and cost-effective technology, like the solar-powered pump, is an easy way to address this issue because of how expensive for oil companies to minimize the impact by pumping the leftovers. For Olobiri oil well 17, this paper proposed intensive system sizing. The PVsyst made recommendations for the pump's size, and the software's performance was assessed by simulating an oil depth to account for the site's specifications. According to the software, the system and pump efficiencies are 11.4% and 37.9% for 5 hours of running time. Also, 5% of system efficiency and 11% of pump efficiency were indicated when there was a continuous flow. To properly size the PV setup in HOMERpro, the overall load of the entire power system was considered. According to the PVsyst Suggestion, the software recommended a PV unit of 50 kW and 54.9 kW for working conditions with exact size specifications for batteries. However, the system running for 5 hours is more efficient when compared.

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