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Reengineering a Water Supply Scheme with a Hybrid Energy Source in the Niger Delta, Nigeria

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Abstract

This paper reports the reengineering of an existing water supply scheme to include a treatment system and a hybrid energy system which combines solar energy and a diesel-generator energy source that would enable provision of potable water for Gokana, Rivers State, Nigeria. The existing scheme is reengineered to serve a projected population of 389,155 persons with an estimated water demand of 0.97m^3/s. The diesel-generator is used to power the submersible pumps and the solar energy is used to power the water treatment system and a surface pump. The submersible pumps are selected to operate at a total capacity of 1.01m^3/s, head of 65m and required total power of 770kW, to pump raw water from the aquifer into a 21900m^3 raw water tank in 6 hours per day. The surface pump is selected to operate at a capacity of 0.04m^3/s, head of 16m and power of 8kW, to pump treated water into a 540m^3 overhead tank in 4 hours per day, from where it is delivered by gravity into the distribution system. The Google map of Gokana was loaded to EPANET software and simulated to show the flows and pressures in the distribution system. The 162kWh/day of energy required from the solar system would require a total of 135 solar panels, covering an array area of 262m^2. The peak power of the array amounted to 44kW and the energy generated would be stored in an 500kWh battery storage system. The bill of engineering measurements showed that the reengineered water supply scheme can be implemented at a cost of ₦132, 682, 990.

Keywords: EPANET Simulation on Google Map of Gokana; Existing Water Supply Scheme (EWSS); Hybrid Energy System; Reengineered Water Supply Scheme (RWSS); Total Dynamic Head .

1. Introduction

Water is a basic need for mankind and it has several available sources. Groundwater constitutes the largest readily available fresh water reserve on earth. It plays an essential role in the domestic water supply system for small towns and rural regions, where it represents a relatively clean, reliable and cost-effective resource [1]. Groundwater undergoes natural filtration as it flows downward through layers of the soil into its storage, thus requiring only chlorination and treatment to address non-health-related parameters, such as excessive hardness or discoloration caused by iron and manganese [2]. However, for potable water, other concerns arise as groundwater is likely to contain traces of organic compounds that pose potential long-term health risks [3].

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According to United Nations Environmental Program (UNEP) the groundwater in the Niger Delta region of Nigeria, especially Gokana in Ogoni, the study area, is highly contaminated with dangerous concentrations of benzene and other hydrocarbons, which is an environmental consequence of decades of oil exploration activities [4]. Thus, groundwater in the study area requires pumping and treatment facilities to make for potable use and this requires various technologies which use energy.

Solar-based technologies have been found to be in the best interest of communities considering its environmental friendliness, availability, sustainability, efficiency and cost effectiveness [5]. Thus, in order to ensure the availability of sufficient quantities of good quality water, it becomes imperative in Nigeria, with its unstable electricity supply, to design water supply systems with hybrid energy that blend solar energy and diesel generator energy sources.

The author in [6] presented a paper on solar-powered groundwater pumping systems for Nigerian water sheds. The paper discussed the occurrence of different groundwater sheds, viability of solar-powered groundwater pumping systems and their economic analyses. He concluded that groundwater pumping using photovoltaic (PV) systems appeared to be a viable means of providing water for the Nigerian populace.

The authors in [7] designed a water distribution system using EPANET software. The work highlighted the process carried out in the design of a water supply system for Kathgarh, India. With the aid of all relevant information of the area and EPANET software, a proper water supply system that efficiently met the daily water requirement of the area was designed.

The authors in [8] presented a paper on dynamic modelling of solar water pumping systems with energy storage. They developed a dynamic model for both battery-less and battery-based systems running a motor-pump set using solar energy to lift groundwater in MATLAB/ Simulink. They observed the responses in pump speed and water discharge rate with the changes in solar irradiance and ambient temperature. The result showed only 10% variation in rotor speed and water discharge rate for both systems for the varying solar irradiances. They concluded that the solar water pumping system can be integrated into irrigation systems and other water supply systems as it is an economically feasible solution for long periods.

The authors in [5] reviewed a sustainable solar-powered water supply system design approach. The paper reviewed steps in the design process of solar powered water supply system and demonstrated the technological viability and cost effectiveness for delivering safe water to people, particularly in rural areas using their design approach. Their approach was conventional but relatively unique in engineering specifications in terms of hydraulics, power requirement, water treatment and distribution having tested them in different geographical environments. They highlighted advantages and disadvantages of the design approach and presented recommendations, concluding that the approach can be replicated elsewhere as a water supply solution.

The authors in [9] designed a micro system using solar energy to supply drinking water to a health post. The design was compared and verified with the system's existing design prepared by a development agency, and they concluded that solar pumping water supply systems were cost-effective and environmentally friendly.

The authors in [10] provided a comprehensive study for the design of solar pumping system components with different water demands. A computer program was developed for the simulation of the system and the calculation of hydraulic power, PV peak power, PV required area, and total system costs for different total dynamic heads and different water demands ranging from 1 to 1000m^3/day. The result showed that solar water pumping systems were more economically feasible than diesel generators for water demand up to100m^3/day.

The authors in [11] presented a field-performance investigation on an integrated solar water supply system for two areas in Thailand that experienced severe draughts, and water supply was becoming a major issue. A 15kW solar submersible pump and a stand-alone 15.36 kW solar power supported by four solar trackers were installed to lift water from the two areas that have static heads of 64m and 48m, respectively to two reservoirs of 1000m^3 and 1800m^3 capacities, at an average flow rate of 300m^3 and 400m^3 per day, respectively as a water supply solution.

Having reviewed relevant literatures, the solar-powered water supply system appears to be a viable means of providing water for the Nigerian populace experiencing unstable power supply. This paper reports the reengineering of an existing water supply scheme (EWSS) to include a water treatment plant, solar-power system and other design improvements that would enable the provision of potable water as recommended by UNEP for Gokana, Rivers State, Nigeria [4]. The reengineering includes estimation of the water demand and the required storage capacity, rating and selecting suitable pumping systems, selecting a suitable water treatment process, designing a distribution system using EPANET software, sizing the PV array, battery storage system, inverter and charge controller, and estimating the cost of installation.

2. Materials and Methods

The materials for this study include years 1991 and 2006 de facto census results of Gokana, Google satellite map of Gokana, solar irradiation data of Gokana, pump catalogues and EPANET software. The methods that have been used in the study are discussed in the following sections:

2.1 Case study

This study takes the existing water supply scheme (EWSS) located in Gokana Local Government Area, Rivers State, Nigeria as case study.

2.1.1 Description of the study area

Gokana, Ogoni, Rivers State is a region in the Niger Delta covering an area of about 126 km^2 and is divided into seventeen communities. Gokana is located 54km southeast of Port Harcourt on latitude 4.7°N and longitude 7.3°E with an average elevation of 18m above sea level, and daily sunshine hours of 6.5 hours [12]. The static water level in the area occurs at 6.1m below ground surface [13]. The 1991 and 2006 census results put the population of Gokana at 159, 461 and 233, 813, respectively [14]. The Google satellite map of Gokana is shown Figure 1.

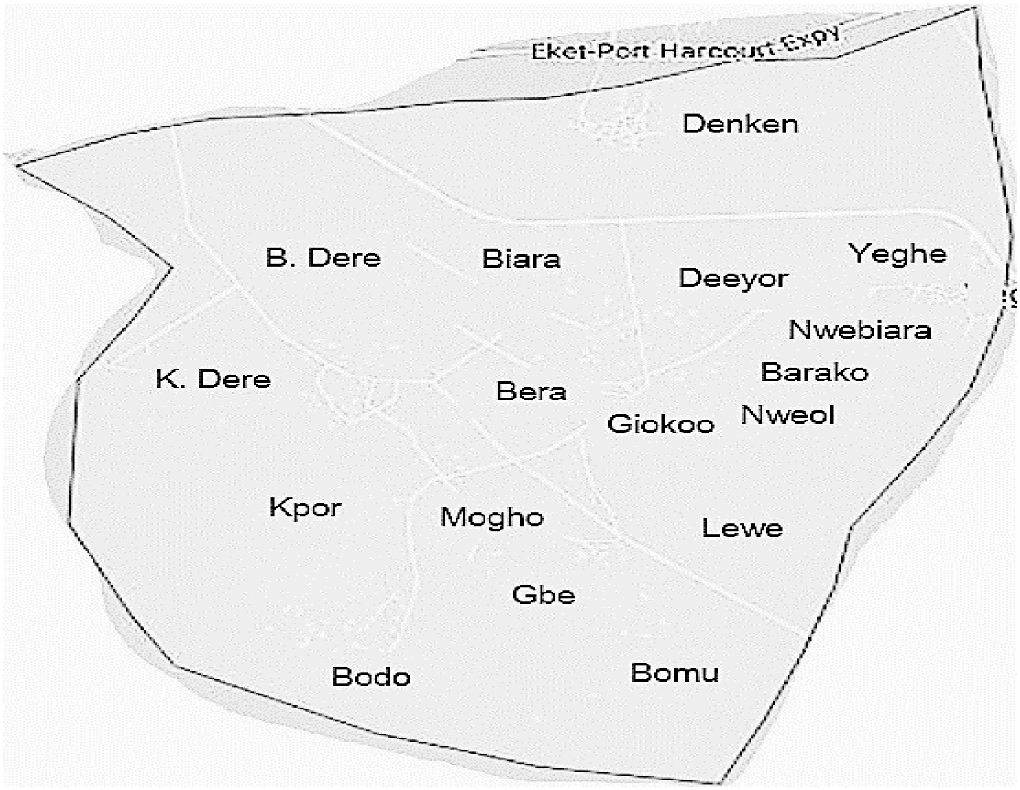

Figure 1: google satellite map of Gokana.

2.1.2 Description of the existing water supply scheme (EWSS)

Table 1 shows the design summary of the EWSS in Gokana obtained through a survey conducted by the authors.

Table 1: Design summary of the existing water supply system.

Engineering specifications	Value
Submersible Pump:	
Discharge Size	152.4*mm* (6″)
Delivery	0.0726m^3/s (1150 GPM)
Discharge Level (Vertical Rise)	15.9*m* (52*ft*), with 254*mm* (10″) HDPE Pipe
Suction Level (Pumping Level)	6.1*m* (20*ft*)
Number of Pumps	4, connected in parallel, each is 6.096*m* (20*ft*) from tank
Source of Power	100*kVA* Diesel Generator
Pipe Size:	
Mainline	304.8*mm* (12″) HDPE pipe
Submain Line	152.4*mm* (6″) HDPE pipe
Branches	101.6*mm* (4″) HDPE pipe
Number of Public Faucets	3 per community
Water Storage Capacity	540m^3 (540,000*litres*) elevated galvanized steel sectional tank, operated on fill-and-draw

2.2 Description of the reengineered water supply scheme (RWSS)

The EWSS is reengineered to include a water treatment system, solar energy system and other design improvements that would enable the provision of potable water of standard recommended by UNEP [4]. Figures 2 and 3, illustrate the pumping of groundwater using the hybrid energy system. Raw water is pumped from an aquifer into a raw water tank using submersible pumps, and it is delivered into the treatment plant. Treated water is pumped using a surface pump into an overhead treated water tank from where it is delivered into the distribution system by gravity. The key components within the RWSS include:

2.2.1 Water treatment system

Raw water delivered into the treatment plant as shown in Figure 2, undergoes seven processes including aeration process that is designed to achieve efficient mass transfer of oxygen into the raw water for removal of gases and volatile compounds, by air stripping as recommended by UNEP for the provision of potable water free of hydrocarbons [4].

2.2.2 Hybrid energy system

Hybrid energy systems are combinations of two or more energy conversion devices [15]. The system employed in this study combines solar energy and diesel generator energy sources and operates as explained in the schematic diagram of Figure 3. The system components include the PV array, battery storage system (BSS), inverters, charge controller, diesel generator and other installation hardware. The design of a water supply system which incorporates a solar energy system requires obtaining solar energy data which include the global horizontal irradiation that is available for solar energy generation. According to energy sector management assistance program, the global horizontal irradiation for Gokana is 4.3kWh/m^2 per day [16].

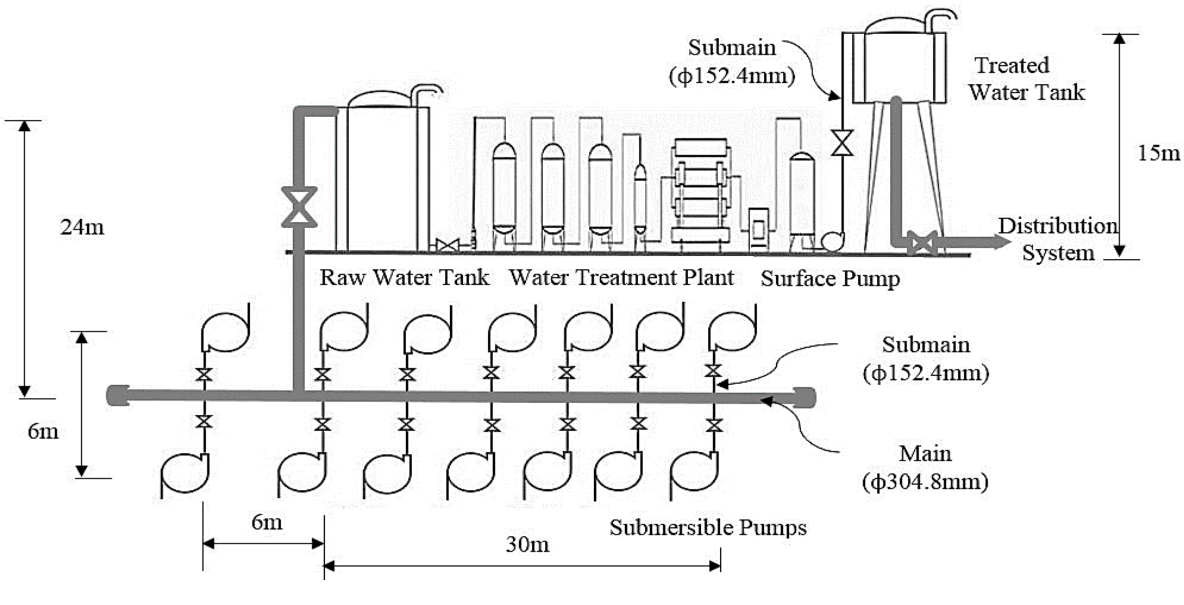

Figure 2: schematic of the reengineered pumping system.

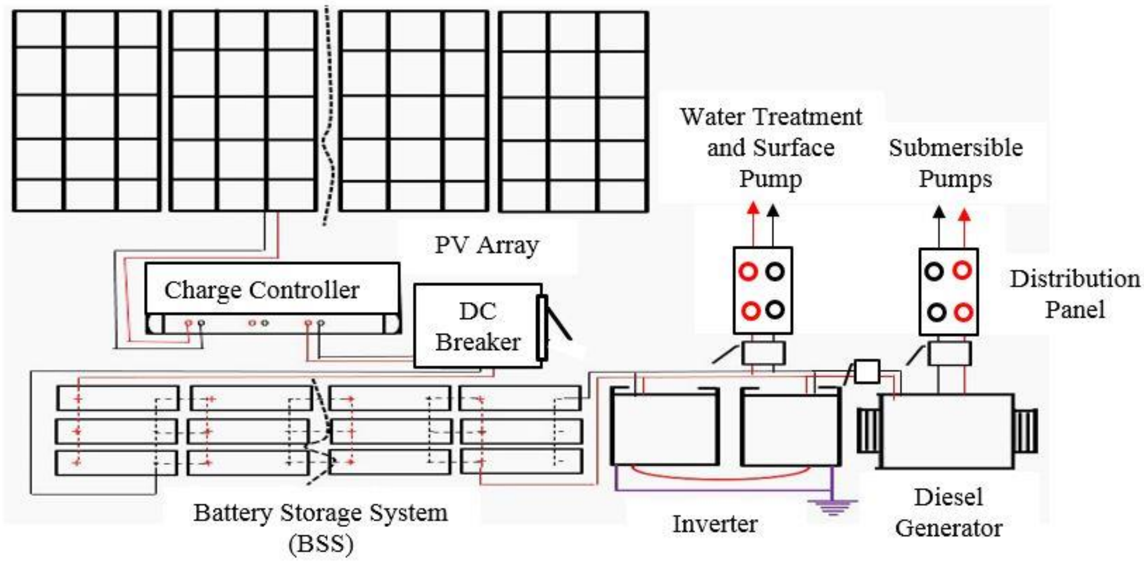

Figure 3: schematic of the hybrid energy system**.**

2.2.3 Distribution system

The RWSS is designed to distribute treated water from the treatment plant to the consumers using the dead-end distribution system. In this distribution system the size of the main line decreases as its distance from the source increases, in consideration that the farther pipes have to carry less water. The system is designed with high density polyethylene (HDPE) pipe owing to the advantage of its smooth internal surface and resistance against corrosion, tuberculation and deposits [17]. In the design of the distribution system, pipe network analysis is carried out to determine the flow rates and pressure drops in each pipe using EPANET as shown in Figure 4. EPANET is a computer program that performs simulation of hydraulics of water distribution systems within pressurized pipe networks. EPANET tracks the flow of water in each pipe and the pressure at each node [18].

2.3 Estimation of water demand

The estimation of water demand for an area required the following factors:

2.3.1 Design period

A water supply system is designed such that it has a provision for sufficient capacity to meet the demand for a reasonable future period. Water supply system are designed for a period of 10 to 30 years [17].

2.3.2 Population forecast

Water supply system is designed to meet not only the present requirements but also the future requirements. As such it is essential to know the present population of the area and also to forecast the future population. Geometrical increase method is used to forecast the population of an area for water supply system within 20 years and the forecasted population (P_t) using geometrical increase method given as [19]

$$P_t = P_o(1+r)^n \tag{1}$$

where P_o = present population, r = growth rate of the population, n = design period (years).

Growth rate of the population is given as [18]

$$r = \left(\frac{P_o}{P_p}\right)^{\frac{1}{N}} - 1 \tag{2}$$

where P_p = past population, N = number of years between successive censuses.

Rate of demand (per capita demand)

Rate of demand or per capita demand is the average amount of daily water required by one person. According to United Nations the per capita water demand in Nigeria is 216 l/c/d [20]. The total water demand (W_t) in liters per day (*l/d*) is given by the expression [20]

$$W_t = P_t q \tag{3}$$

where q = per capita water demand (*l/c/d*).

2.4 Sizing of the water storage tank

The RWSS is designed with a reinforced cement concrete (RCC) tank for the raw water storage, and elevated galvanized steel tank for the treated water storage, both operated on fill-and-draw. In a fill-and-draw system, water is pumped directly into the storage tank at a high pumping rate and distributed through gravity. As a rule of thumb, the capacity of a storage tank (C_t) in a water supply system is expressed in litres and is given as [17]

$$C_t = 0.25W_t \tag{4}$$

2.5 Sizing of the pumps

Pump sizing is essential to ensure efficient and reliable operation at a specified head and flow rate. Thus, sizing of a pump requires the determination of the following:

2.5.1 Flow rate

Flow rate (Q_t) can be determined by dividing the capacity of a storage tank by the pumping time, and is expressed as [21]

$$Q_t = \frac{C_t}{t_p} \tag{5}$$

where t_p = pumping time (hours).

2.5.2 Pump installation

The submersible pumps in the RWSS are installed in parallel as shown in Figure 2. The distance between the pumps is set at 6m, which is the optimal distance between boreholes [22]. The number of pumps (N_p) required in the system is given as [23]

$$N_p = \frac{Q_t}{Q} \quad (6)$$

where Q = delivery of each submersible pump (m^3/s).

2.5.3 Static head

The static head measures the total vertical distance that a pump raises water. It is the difference in elevation between suction level and discharge level. Static head (h_s) for the submersible pump is given as [24]

$$h_s = Z_s + Z_d \quad (7)$$

where Z_s = suction level (m), Z_d = discharge level (m).

2.5.4 Friction head

Friction head is the amount of energy loss due to friction of the fluid moving through pipes and fittings. Friction head losses due to pipe (h_p) can be estimated with the Hazen-Williams equation given as [17]

$$h_p = 10.7 \times \left(\frac{Q}{C}\right)^{1.852} \times \frac{L}{D^{4.87}} \quad (8)$$

where C = Hazen-Williams roughness constant, D = diameter of pipe (m), L = length of pipe (m). Hazen-Williams roughness constant for PVC/PE pipe is 150.

Friction head losses due to fittings and valves (h_m) vary with the velocity head and is generally related to a coefficient by the equation [24]

$$h_m = 0.08256 K Q^2 D^{-4} \quad (9)$$

where K = loss coefficient for a valve or fitting. The values of K for various fittings and valves are given by Hydraulic Institute [25]. When multiple valves and fittings in a pipeline have the same diameter, the K values for each valve or fitting can be added together [26]

Total friction head loss in a pipe line (h_f) is given as [25]

$$h_f = h_p + h_m \quad (10)$$

2.5.5 Velocity head

Velocity head is the change in kinetic energy of water from source to discharge point. Velocity head (h_v) is given as [24]

$$h_v = 0.08256 Q^2 D^{-4} \tag{11}$$

2.5.6 Total dynamic head

The total dynamic head (H) of a water system determines the various head losses that the pump must overcome. It is the sum of static head, friction head and velocity head at the point of discharge, and is given as [17]

$$H = h_s + h_f + h_v \tag{12}$$

2.5.7 Pump power

The power (P) required by the pump is expressed as [27]

$$P = \frac{\rho g Q H}{\eta} \tag{13}$$

where ρ = density of water (1000 kg/m^3), g = acceleration due to gravity (9.81m/s^2), η = hydraulic efficiency of the pump.

2.5.8 Pump selection

By repeating the calculation for the friction head and velocity head for a range of flows, a system characteristic curve that define the relationship between total dynamic head and flow rate can be plotted. The selection of a suitable pump requires superimposing this system characteristic curve onto the pump characteristic curves. The point of interception of the curves for the selected pump is the operating point of the system [6].

2.6 Sizing of the PV array

The PV array is sized to supply power to the surface pump and the water treatment plant. The required size of the PV array depends on the pump power and the solar irradiation available at the area. The modules of the PV array are connected both in series and parallel to minimize energy losses in a large PV array [28]. The PV array area (A_{pv}) and the peak power (P_{pv}) are respectively, given as [6]

$$A_{PV} = \frac{E \times S_f}{G_{av} \times \eta_{PV} \times TCF} \tag{14}$$

and

$$P_{PV} = A_{PV} \times G_{ref} \times \eta_{PV} \tag{15}$$

where E = energy required from the PV module daily (kWh/day), S_f = safety factor =1.25, G_{av} = daily average irradiation on a horizontal surface (kW/m^2), η_{pv}= PV energy conversion efficiency, TCF = temperature correction factor, G_{ref} = solar irradiation at standard test condition amounting to 1kW/m^2. TCF that corresponds to the average annual ambient temperature of 26.5°C experienced in Gokana is 1.07 [29].

The total number of modules (N_m) in the PV array is given by

$$N_m = \frac{A_{PV}}{A_m} \tag{16}$$

where A_m = area of each module (m^2)

The number of modules to be connected in series (N_{ms}) and parallel (N_{mp}) of the PV array are given respectively as [30]

$$N_{ms} = \frac{V_s}{V_{mp}} \tag{17}$$

and

$$N_{mp} = \frac{N_m}{N_{ms}} \tag{18}$$

where V_s = system voltage (V), V_{mp} = maximum power voltage (V).

2.7 Sizing of battery storage system (BSS)

The energy harvested from the PV array is stored in a BSS. Sizing of the BSS requires the determination of the output voltage of the PV array which is proportional to the daily load, and is based on the battery capacity selected for the system. The required energy storage capacity of the BSS expressed in Watt-hour (Wh) and Ampere-hours (Ah), respectively, are given as [31]

$$C_{Wh} = \frac{E \times DOA}{DOD \times \eta_b \times \eta_{inv}} \tag{19}$$

and

$$C_{Ah} = \frac{C_{Wh}}{V_s} \tag{20}$$

where C_{Wh} = energy storage capacity (Wh), DOA = numbers of days of autonomy, DOD = battery depth of discharge, η_b= battery efficiency (%), η_{inv} = inverter efficiency (%), C_{Ah} = energy storage capacity (Ah).

The number of batteries to be connected in series and parallel of the BSS are given respectively as [30]

$$N_{BS} = \frac{V_s}{V_b} \tag{21}$$

and

$$N_{BP} = \frac{C_{Ah}}{C_b} \tag{22}$$

where N_{BS} = number of batteries to be connected in series, V_b = voltage rating of a single battery (V), N_{BP} =number of batteries to be connected in parallel, C_b = energy capacity of a single battery (Ah).

The total number of batteries (N_B) required for BSS is then given as [30]

$$N_B = N_{BP} \times N_{BS} \tag{23}$$

2.8 Sizing of inverter

Inverters are connected in parallel and total number of inverters (N_{inv}) required for the system is given as [30]

$$N_{inv} = \frac{P_{PV} \times Pf}{P_{inv}} \tag{24}$$

where Pf = power factor, P_{inv} = power capacity rating of a single inverter (kVA).

2.9 Sizing of charge controller

Charge controllers are connected in parallel to meet high power charging requirements and total number of charge controllers (N_{ch}) required is given as [30]

$$N_{ch} = \frac{I_{SC} \times Pf \times N_{mp}}{I_{ch}} \tag{25}$$

where I_{sc} = short circuit current of the PV module (A), I_{ch} = current rating of a single charge controller (A). The specifications of the PV module, battery, inverter and charge controller used are listed in Table 2.

Table 2: Specifications of PV, battery, inverter and charge controller.

Component	Parameter	Value
PV (330W Mono Solar Panel)	Maximum power voltage	37.4*V*
	Maximum system voltage	1000*V*
	Short circuit current	9.39*A*
	Panel efficiency	16.80%
	Dimension	1956*mm* x 995*mm* x 40*mm*
Battery (lithium battery)	Voltage	48*V*
	Capacity	200*Ah*
	Depth of Discharge	80%
	Efficiency	90%
Inverter (pure sine wave)	Capacity	30*kVA*
	Efficiency	90%
Charge Controller (MPPT)	Current	100*A*

Source: [32]

3. Results and Discussion

The results of the study are presented and discussed as follows:

3.1 Analysis of the water demand

Applying Equation 2, the growth rate of the population is determined as follows: P_p = 159,461 P_o= 233,813, N = 2006 – 1991 = 15years

$$r = \left(\frac{233813}{159461}\right)^{\frac{1}{15}} - 1 = 0.0258$$

Applying Equation 1, we obtain the forecasted population:

$$P_t = 233813(1 + 0.0258)^{20} \approx 389155$$

Using Equation 3, noting that q = 216*l/c/d*, we obtain:

$$W_t = 389155(216) \approx 84057467 \ l/d = 0.97 m^3/s$$

3.2 Analysis of the raw water storage tank capacity

Applying Equation 4, noting that W_t = 84057467 *l/d*, gives:

$$C_t = 0.25 \times 84057467 \approx 21900 m^3$$

$$\approx 35m \times 26m \times 24m$$

3.3 Analysis of the flow rate of the submersible pumps

Applying Equation 5, where C_t = 21900m^3 and t_p = 6h (schedule pumping time) gives:

$$Q_t = \frac{21900}{6} \approx 3650m^3/h \approx 1.01m^3/s$$

3.4 Analysis of the required number of pumps

Applying Equation 6, the required number of pump is determined as follows: Q_t = 1.01m^3/s, Q = 0.0726m^3/s (from Table1)

$$n_p = \frac{1.01}{0.0726} \approx 14$$

From Table 1, the delivery (Q) of each of the four (4) submersible pumps in the EWSS is 0.0726m^3/s. Thus, the RWSS would require an additional ten (10) submersible pumps of the same capacity to serve a projected population of 389155, with a projected water demand of 0.97m^3/s, for a design period of 20 years. This analysis provides an optimistic estimation of water demand by the populace for up to year 2041, as an adequate water supply solution to tackle the potable water supply problem reported in the study area.

3.5 Analysis of the total dynamic head of the submersible pumps

The total dynamic head of the submersible pumps is analyzed as follows:

(i) Static Head

Using Equation 7, the static head is calculated thus: Z_s = 6.1m (from Table 1), Z_d = 24m (height of raw water tank),

$$h_s = 6.1 + 24 \approx 30.1m$$

(ii) Friction head losses due to pipe

The pipes used in the pumping system of the RWSS are the main and Submain as shown in Figure 2. The main connects all the submersible pumps and rise the water into the raw water tank, and the submain is used as the pump discharge pipe into the main.

Applying Equation 8, friction head loss due to the main is determined as follows: Q = 1.01m^3/s, D = 0.3048m, C = 150, L = 30m + 24m = 54m (as, from Figure 2, the farthest pump is 30m away)

$$h_p = \left\{ \frac{10.7}{150^{1.852}} \times 1.01^{1.852} \times \frac{54}{0.3048^{4.87}} \right\} \approx 17.89m$$

Also, applying Equation 8, Friction head loss due to the submain is determined as follows: Q= 0.0726m^3/s, D = 0.1524m, C = 150, L = 3m (from Figure 2)

$$h_p = \left\{ \frac{10.7}{150^{1.852}} \times 0.0726^{1.852} \times \frac{3}{0.1524^{4.87}} \right\} \approx 0.22m$$

Thus, friction head losses due to pipes is determined as:

$$h_p = 17.89 + 0.22 = 18.11m$$

(iii) Friction head losses due to fittings and valves

Applying Equation 9, where $K_{90^o elbow}$= 0.16, K_{Tee}= 0.01, K_{Union} = 0.04, $K_{Gatevalve}$= 0.17, K_{Non} = 1.3, $K_{Reducer}$ = 0.05 (Hydraulic Institute,1990) the friction head losses due to fittings and valves for the main are calculated thus: Q = 1.01m^3/s, D = 0.3048m (from Table 1)

$$h_m = 0.08256 \times 1.01^2 \times 0.3048^{-4} \times \{(7 \times 0.01) + 0.16 + 0.17 + (2 \times 0.04)\} \approx 4.684m$$

Also, the friction head losses due to fittings and valves for the submain is calculated thus: Q = 0.0726m^3/s, D = 0.1524m (from Table 1)

$$h_m = 0.08256 \times 0.0726^2 \times 0.1524^{-4} \times \{1.3 + 0.05\} \approx 1.089m$$

Thus, the friction head losses due to fittings and valves for the two pipes is determined as:

h_m = 4.684 + 1.089 = 5.773m

Applying Equation 10, we obtain the friction head, noting that h_p = 49.14m, h_m = 21.58m,

h_f = 18.11 + 5.773 = 23.88m

(iv) Velocity head

Applying Equation 11, the velocity head due to the main is calculated thus: Q = 1.01m^3/s, D = 0.3048m(from Table 1)

$$h_v = 0.08256 \times 1.01^2 \times 0.3048^{-4} \approx 9.8m$$

and the velocity head due to the submain is calculated thus: Q = 0.0726m^3/s, D = 0.1524m (from Table 1)

$$h_v = 0.08256 \times 0.0726^2 \times 0.152^{-4} \approx 0.8m$$

Thus, the velocity head losses for the two pipes is determined as: h_v = 9.8m + 0.8m = 10.6m

Applying Equation 12, we obtain the total dynamic head, noting that h_s = 30.1m, h_f = 23.88m, h_v = 10.6m,

H = 30.1m +23.88m + 10.6m ≈ 65m

3.6 Analysis of submersible pumps power requirements

Applying Equation 13, where ρ = 1000kg/m^3, g = 9.81m/s^2, Q = 0.0726m^3/s, H = 65m, η = 0.84 (from system curve plotted), we obtain the power requirements of the submersible pumps as

$$P = \frac{1000 \times 9.81 \times 0.0726 \times 65}{0.84} = 55111W \approx 55kW$$

Each submersible pump in the RWSS is selected to operate at a capacity of 0.0726m^3/s, head of 65m and power of 55kW. Thus, the 14 submersible pumps connected in parallel would operate at a total capacity of 1.01m^3/s and head of 65*m*, and would require a total power of 770*kW*. This analysis showed that when multiple pumps operates in a parallel pumping system more energy is required. However, a greater increase in flow rate is advantageous to meeting the water demand.

3.7 Analysis of the flow rate of the surface pump

Applying Equation 5, where C_t = 540m^3 (from Table 1) and t_p = 4*h* (schedule pumping time), we obtain the flow rate of the surface pump as

$$Q = \frac{540}{4} \approx 135m^3/h \approx 0.04m^3/s$$

3.8 Analysis of the total dynamic head of the surface pump

The total dynamic head of the surface pump is analyzed as follows:

(i) Static head

From Figure 2, the Static head (h_s) is the vertical rise of the surface pump and is given as 15*m*: h_s = 15*m*

(ii) Friction head due to pipe

Applying Equation 8, the friction head losses due to the submain pipes used for the surface pump discharge are determined as follows: Q = 0.04m^3/s, C = 150, L = 15*m*, D = 0.1524*m* (from Figure 2)

$$h_p = \left\{ \frac{10.7}{150^{1.852}} \times 0.04^{1.852} \times \frac{15}{0.1524^{4.87}} \right\} \approx 0.37m$$

(iii) Friction head losses due to fittings and valves

Applying Equation 9, where $K_{90^o elbow}$ = 0.45, $K_{Gatevalve}$= 0.17, (Hydraulic Institute,1990) the friction head losses due to fittings and valves for the submain pipes used for the surface pump discharge is calculated thus: Q = 0.04m^3/s, D = 0.1524*m* (from Figure 2)

$$h_m = 0.08256 \times 0.04^2 \times 0.1524^{-4} \times \{0.45 + 0.17\} \approx 0.15m$$

Applying Equation 10, we obtain the friction head, noting that h_p = 0.37*m*, h_m = 0.15*m*,

$$h_f = 0.37 + 0.15 = 0.52m$$

(iv) Velocity head

Applying Equation 11, the velocity head due to the submain pipes used for the surface pump discharge is calculated thus: Q = 0.04m^3/s, D = 0.1524*m* (from Figure 2)

$$h_v = 0.08256 \times 0.04^2 \times 0.1524^{-4} \approx 0.25m$$

Thus, applying Equation 12, we obtain the total dynamic head of the surface pump:

$$H = 15m + 0.52m + 0.25 \approx 16m$$

3.9 Analysis of surface pump power requirements

Applying Equation 13, the surface pump power requirement is determined as follows: ρ = 1000kg/m^3, g = 9.81m/s^2, Q = 0.04m^3/s, H =16m, η = 0.8 (from system curve plotted),

$$P = \frac{1000 \times 9.81 \times 0.04 \times 16}{0.8} = 7848W \approx 8kW$$

Thus, the surface pump in the RWSS are selected to operate at a capacity of 0.04m^3/s, head of 16m and power of 8kW

3.10 Analysis of the distribution system

Figure 4 is the google map of Gokana loaded to EPANET and Simulated to show the flow and pressure in the pipe network of the distribution system

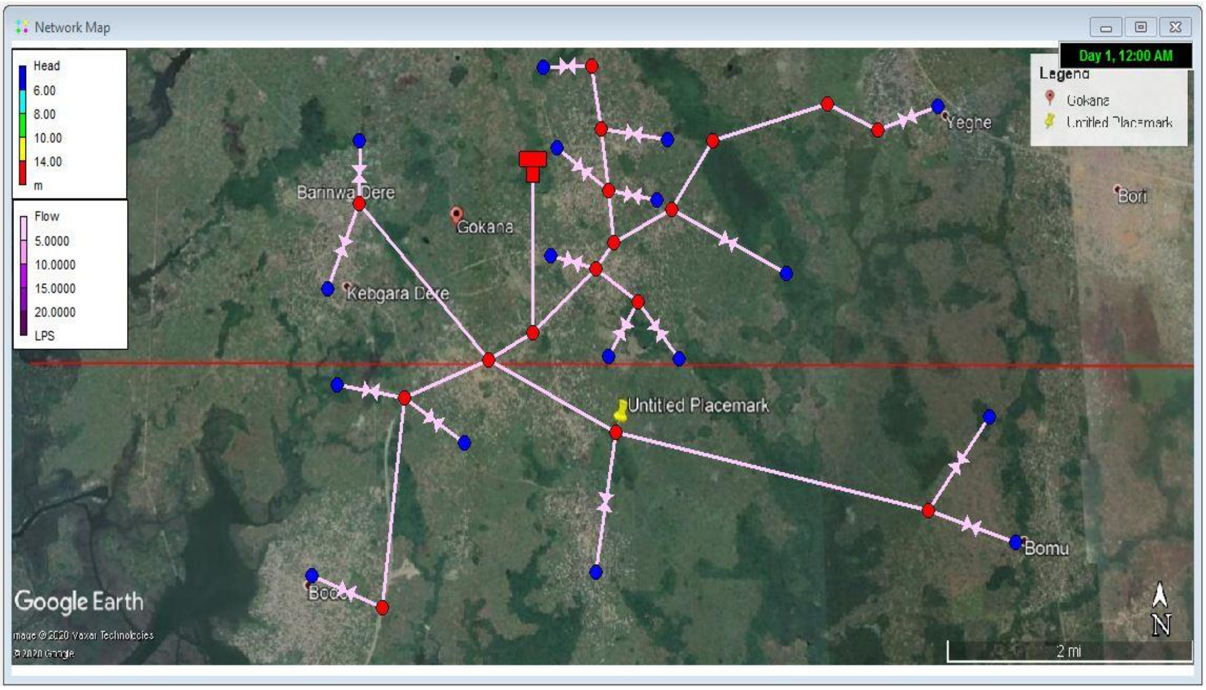

Figure 5: EPANET simulation showing the flow and pressure in the distribution system.

3.11 Analysis of energy required from the PV array

The PV array is used to power the surface pump and the water treatment plant. The surface pump power requirement is 8kW, and the water treatment plant power requirement is 5.5kW (manufacturer's specification). Thus, energy required from the PV module for 12 hours water supply per day, (E) = $12\ (8 + 5.5) \approx 162kWh/day$.

Using Equation 14, the PV array area is calculated as follows: E = 162kWh/day, S_f = 1.25, G_{av} = 4.3$kWh/m^2/day$, TCF = 1.07, η_{pv} = 0.168 (from Table 2)

$$A_{PV} = \frac{162 \times 1.25}{4.3 \times 0.168 \times 1.07} \approx 262m^2$$

Applying Equation 15, where A_{pv} = 262m^2, G_{ref} = 1kW/m^2, η_{pv} = 0.168, we obtain the peak power from the PV array

$$P_{PV} = 262 \times 1 \times 0.168 = 44.016W \approx 44kW$$

using Equation 16, the total number of modules in the PV array is calculated as follows: A_{PV} = 262m^2, $A_m = 1.956m \times 0.995m = 1.946m^2$ (from Table 2)

$$N_m = \frac{262}{1.946} \approx 135$$

Applying Equations17 and 18, the numbers of modules to be connected in series and parallel of the PV array are respectively calculated thus: V_s = 1000V, V_{mp} = 37.4V (from Table 2), N_m = 135

$$N_{ms} = \frac{1000}{37.4} \approx 27$$

and
$$N_{mp} = \frac{135}{27} = 5$$

The 162*kWh/day* of energy required from the solar system would require a total of 135 solar panels, with 27 of the panels connect in series in 5 parallel strings, and covering an array area of 262m^2.

3.12 Analysis of the required capacity of BSS

Applying Equations 19 and 20, where E = 162kWh, DOA = 2, DOD = 0.80, η_b= 0.90, η_{inv} = 0.9, V_s = 1000V (from Table 2), the energy storage capacity in Watt-hour and Ampere-hour are respectively, calculated thus:

$$C_{Wh} = \frac{162 \times 2}{0.8 \times 0.9 \times 0.9} \approx 500kWh$$

and
$$C_{Ah} = \frac{500000}{1000} = 500Ah$$

Applying Equations 21, 22 and 23, noting that V_s = 1000V, V_b = 48V (from Table 2), C_{Ah} = 500Ah, C_b = 200Ah, the total number of batteries required for BSS are calculated thus:

$$N_{BS} = \frac{1000}{48} \approx 21, \quad N_{BP} = \frac{500}{200} \approx 3$$

$$N_B = 21 \times 3 = 63$$

The 500kWh energy storage capacity of the BSS contains 63 batteries of 48V, 200Ah capacity each, which are wired into 3 parallel string.

3.13 Analysis of the required number of inverters and charge controllers

Applying Equation 24 and 25, where P_{PV} = 44kW, Pf = 1.25, P_{inv} = 30kVA, I_{SC} = 9.39A (from Table 2), N_{mp} = 6, I_{ch} = 100A, the total number of inverters and charge controllers required for the system are respectively calculated thus:

$$N_{inv} = \frac{44 \times 1.25}{30} \approx 2$$

and

$$N_{ch} = \frac{9.39 \times 1.25 \times 6}{100} \approx 1$$

Thus, a total of 2 inverters of 30kVA capacity and 1 charge controller of 100A capacity are required for the system.

3.14 Cost of implementation

The summary of the Bill of Engineering Measurements and Evaluations of the re-engineered water supply scheme is as shown in Table 3

Table 3: Summary of bill of engineering measurements and evaluations of the RWSS.

S/N	Description	Qty	Rate(₦)	Cost(₦)
1	Preliminaries and Community Engagement and Mobilization		Provisional Sum	1, 000, 000
2	Pipe Work and Rehabilitation of Existing Pipe Network		Lump Sum	2, 000, 000
3	Provision and Installation of 21900m^3 Raw Water Tank	1	Lump Sum	15, 000, 000
4	Rehabilitation of Existing Overhead Treated Water Tank	1	Lump Sum Lump	200, 000
5	Provision and Installation of 5.5kW Water Treatment Plant	1	Sum	27, 700, 000
6	Provision and Installation of 55kW Submersible pumps	10	790,440	7, 904, 400
7	Provision and Installation of 8kW Surface Pump	1	458500	458, 500
8	Provision and Installation of 800kW diesel generator	1	52,500,000	52, 500, 000
9	1956 x 995 x 40mm Solar Panels	135	45000	6, 075, 000
10	100A Charge controller	1	66,420	66, 420
11	30kVA Inverter	2	900,000	1, 800, 000
12	48V, 200Ah Battery	63	245,590	15, 472, 170
13	DC Breaker	1	9000	9, 000
14	AC Breaker	3	4500	13, 500
15	Distribution Panel	2	92,000	184, 000
16	Cable and Accessories		Lump Sum	2, 000, 000
17	Solar Installation Labour		Provisional Sum	200, 000
18	Miscellaneous		Provisional Sum	100, 000
	Total			**132, 682, 990**

4. Conclusion

The findings of the study are summarized as follows:

i. The re-engineered water supply scheme is designed for a sustainable and cost-effective potable water standard recommended by UNEP (2011) for Ogoni. The system is designed to serve a projected population of 389,155 persons with an estimated water demand of 0.97m^3/s (12802*GPM*).

ii. The re-engineered water supply system includes a water treatment plant and a hybrid energy system that combines solar energy and diesel generator energy sources. The diesel generator is used to power the 14 submersible pumps and the solar energy is used to power the water treatment plant and a surface pump.

iii. The fourteen (14) submersible pumps operating at a total capacity of $1.01m^3/s$, head of $65m$ would require a total power of $770kW$, to pump raw water from an aquifer into a $21900m^3$ raw water tank in 6 hours per day, thus requires a diesel generator of 800kW ratings. The surface pump operating at a capacity of $0.04m^3/s$, head of $16m$ and power $8kW$ would be used to pump treated water from the treatment plant into a $540m^3$ overhead treated water tank in 4 hours per day, from where it is delivered by gravity into the distribution system. The Google map of Gokana was loaded to EPANET and simulated to show the flows and pressures in the pipe network of the distribution system.

iv. The 162*kWh/day* of energy required from the solar system to power the water treatment plant and surface pump would require a total of 135 solar panels, with 27 of the panels connect in series in 5 parallel and covering an array area of $262m^2$. The peak power of the array amounts to 44kW.

v. The energy generated will be stored in 500*kWh* BSS, containing 63 batteries of 48*V* and 200*Ah* capacity each, wired into 3 parallel strings.

vi. The bill of engineering measurements and evaluations shows that the re-engineered water supply system can be implemented at a cost of ₦132, 682, 990.

In conclusion, this paper reports the reengineering of an existing water supply scheme to includes water treatment system, solar energy system and other design improvements that would enable provision of sustainable and cost-effective potable water to standards recommended by UNEP for Gokana in Ogoni, Niger Delta, Nigeria.

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