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Design And Evaluation of Grid-Connected Hybrid Storage System Towards Energy Harnessing in University Campuses

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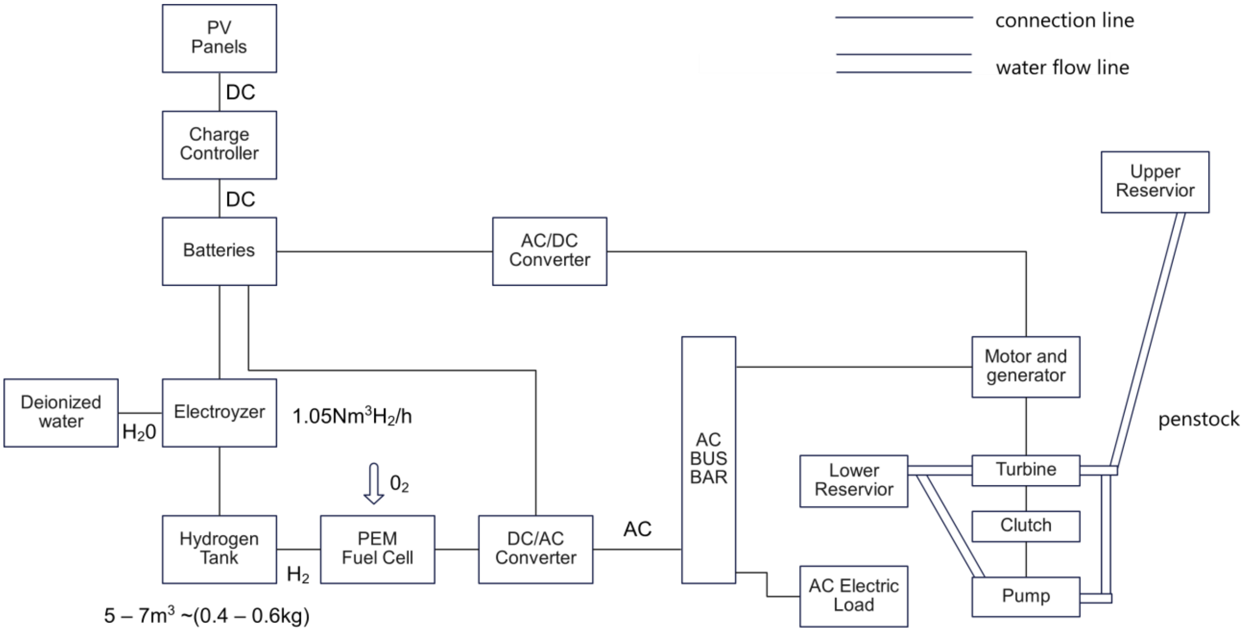
Abstract

The research explores design and analysis of a grid-connected hybrid inexhaustible energy system combining photovoltaic (PV), hydro, and fuel cell technologies with battery and Pumped-Storage Hydroelectricity (PSH)—to address energy challenges at Ambrose Alli University, Nigeria. Persistent electricity shortages and the environmental impact of fossil fuels motivate the adoption of sustainable solutions. The study evaluates different hybrid configurations through modelling and simulation. Key findings reveal that the PV-fuel cell-384V battery system was the most expensive, while the PSH-PV-fuel cell system had the highest operational cost. However, the PSH-PV-fuel cell design outperformed others, generating the highest total power output and exhibiting greater variability. It also achieved superior inverter performance and maintained longer periods of fully charged batteries. Additionally, the PSH system efficiently managed water storage, maintaining reservoirs at 80–100% capacity. Despite higher maintenance costs, the PHS-Photovoltaic-fuel cell system proved to be trustworthy, making it the optimal choice for sustainable energy harvesting in university campuses.

***Keywords**: Hybrid Energy System, Fuel Cell, Pumped-Storage Hydroelectricity, Energy Harvesting, HOMER PRO Software.*

Graphical Abstract



1.0 INTRODUCTION

Presently, the global demand for electrical power is extremely high, prompting this study to explore the combination of various renewable energy systems as a solution to address energy shortages and reduce harmful emissions linked to conventional power generation. Given the critical need to counteract the decline of fossil fuels and lower greenhouse gas output, there is a global shift toward cleaner and more sustainable energy options, including solar, wind, biomass, fuel cells, and hydropower. Renewable energy technologies are now advancing quickly, becoming more cost-effective and efficient, leading to a growing proportion of energy being obtained [1]. Integrating multiple renewable energy systems is feasible depending on the natural resources available in a given region. Solar power, being universally accessible, offers a sustainable solution for electricity generation through photovoltaic (PV) technology, which efficiently converts sunlight into clean energy. However, a key limitation of solar power is its inability to produce electricity during cloudy weather, rainfall, or night-time. To overcome this challenge, combining solar systems with complementary energy sources—such as wind turbines, diesel generators, and energy storage—can enhance overall reliability and performance [2]. In the studied location (university campuses in southern Nigeria), wind energy alone proves inadequate for consistent electricity generation, while diesel generators are unsustainable due to their reliance on finite fossil fuels. As a result, neither system can ensure uninterrupted power supply. A more effective approach involves integrating photovoltaic (PV) systems with hydropower plants and fuel cells (FCs) for enhanced performance. A fuel cell operates as an electrochemical device that transforms the chemical energy from fuels like hydrogen and oxidizing agents such as oxygen into electrical power. [3,4]. Solar and fuel cell energy systems are classified as intermittent renewable sources. This characteristic necessitates immediate consumption of generated power through transmission networks or storage in batteries when production occurs. A significant challenge with solar energy lies in its substantial daily and seasonal fluctuations, particularly in mid-to-high latitude regions. Consequently, effective utilization requires storing solar power in an appropriate medium that allows later conversion into usable electricity as needed is applied [5,6]. Traditional hydropower systems complement solar energy effectively through controllable water release from reservoirs when needed. In locations lacking natural rivers, pumped-storage hydroelectric systems offer an alternative solution. These systems utilize solar-generated electricity to pump water to elevated reservoirs during daylight hours. The stored potential energy is then converted back to electricity during night-time or cloudy conditions by releasing the water through turbines to a lower reservoir, completing a sustainable energy cycle [7]. The combination between photovoltaic (PV), fuel cell (FC) and hydroelectricity hybrid system is studied in this research work, as well as the different storage methods which are the batteries and PSH (Pumped-Storage Hydroelectricity) available for the grid connected hybrid system considered. Nigeria faces a severe energy crisis, with its power sector unable to meet the electricity demands of both households and industries. This failure persists despite the country's vast natural resources, including substantial coal, oil, and gas reserves, as well as its position as Africa's leading oil producer. Shockingly, just 45% of Nigerians have access to the national power grid, and even those connected experience unreliable supply nearly 85% of the time, with some regions having virtually no electricity access. [8,9]. The critical remaining question involves determining Nigeria's most viable energy solution. As identified in research by [10]. The researchers proposed an integrated approach combining multiple energy systems. Their sustainable development model recommends gradually transitioning from fossil fuels to renewable energy while maintaining partial dependence on conventional sources during the shift [11].

2.0 MATERIALS AND METHOD

2.1 System Design and Analysis

Ambrose Alli University, Ekpoma Edo state, is located on Lat 6° 44.3N Long 6° 4.9E in the south-south zone of Nigeria, and has connection to the centralized power distribution network. But due to the challenges facing the nation as mentioned earlier in this study, the power provided is not able to meet the day to day required power capacity of the institution; hence this design aims at providing sufficient energy from a Mini-Grid connected system for the campus using renewable energy sources which are: Photovoltaic Solar Cells with battery storage system, PEM Fuel Cell and Pump Hydroelectricity storage.

In this section, we will first examine the three renewable energy sources individually and their various designs, after which the complete system designs, shall be examined.

Key mini-grid design considerations included analysing the university's energy demand to properly size system components. Daily load consumption was assessed by evaluating both peak (from 8 AM–4 PM, totalling 206.28175MW) and normal demand periods across campus facilities "During off-peak hours (4 PM–7 AM and weekends), the university's power demand drops significantly, as demand is primarily from residential quarters and night time study use in lecture halls.

$$ED = \frac{KWs}{1000} \text{ x n x DF} \quad \text{in} \quad \text{MW} \qquad (1)$$

ED= Energy Demand, KWs is system kilo wattage, n number of appliances, DF is the demand factor.

$$EC = \frac{KWs}{1000} \text{ x n x h} \quad \text{in} \quad \text{MWh} \qquad (2)$$

EC=Total energy consumed, h=number of hours.

2.2. For this study we will be considering 8hours during work days and 6 hours during weekend

Energy consumed a per day = power demand × time(hrs)

Energy consumed during active work week per day = 206.28175MW × 8h = 1650.254MWh

2.3. Load Sharing

From the calculations above, the total load consumed in a day except for weekends will be: 1650.25MWh (N 336m) While during Off peak weekends, the total energy consumed is 4MW* 6=24MWh.

Hence for this system design, we shall work with a daily load consumption of 200MWh as a safety margin and this load will be shared among all the energy sources considered for this design. This will help to determine the specification of the components use for this design. For this design, the photovoltaic system and the fuel cell will be required to provide 150MWh while the PHS system will be required to produce 50MWh of energy.

2.4. Photovoltaic Solar System

This mini-grid employs a centralized photovoltaic system, typically used for large-scale solar generation. The setup includes PV arrays that capture solar energy, connected sequentially to a charge control system, batteries connected in bank configuration, and DC-AC inverter for power conversion. This configuration efficiently transforms sunlight into usable AC electricity.

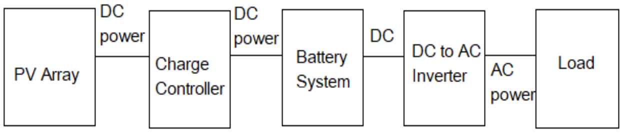


Figure 1.: Typical block illustration of a PV System

Panels Estimation

The load used in this system is the power consumed by all the buildings in the university campus. Energy required from the solar panels is estimated using the formular in (3). The number of solar panels to be used depends on the load requirement. From previous calculation the total energy to be shared.

$$\text{Power from panels} = \frac{\text{Daily Energy Load Consumed}}{\text{Usable Irradiation from Sun (hours)}} \qquad (3)$$

between the photovoltaic system and the fuel cell system is 150MWh. Despite the fact that in Ekpoma there is sunlight all through the year; usable sunlight is only available between the hours of 10am to 4pm which is only 6 hours; if the photovoltaic system is required to provide

50kWh of energy, therefore in [8].

$$\boldsymbol{power\ from\ panels = \frac{50MWh}{6h} \cong 8.33MW} \quad (4)$$

If the panel to be used gives 550watts per panel, the total number of panels needed to produce 8.33kW will be:

$$\boldsymbol{total\ number\ of\ panels = \frac{8.33x10^6}{550} = 15,145.45 panels \approx 15,146 panels} \quad (5a)$$

Hence a safe margin of 15,150 panels will be required to produce 8.33MW power.

Charge Control Configuration

To determine the charge control configuration and input power from panels to the circuitry the formula was employed, below.

$$input\ powe = \frac{output\ power}{efficiency\ (\eta)} \quad (5b)$$

Considering a minimum charge controller efficiency of 85%, the power input to the charge controller can be calculated as follows:

$$nput\ power = \frac{8.33MW}{0.85} = 9.8MW$$

The charge controller rating was calculated with the formula in [9]:

$$charge\ controller\ rating = (input\ power)/(maximum\ voltage\ of\ solar\ panel) \quad (6)$$

The solar panel produces 550W for each solar panel with a maximum voltage of 384V; therefore:

$$charge\ contoller\ rating = \frac{9.8x10^6}{384} = 25520.83A$$

Hence for this research each 116 unit of charge controller rated 220A was used and connected in parallel to handle the input power.

Battery configuration

The battery system was configured as shown;

$$capacity\ (Ah) = \frac{(Daily\ energy\ loads\ consumption\ (Wh))}{(maximum\ panel\ volt\ (v)} \quad (7)$$

Considering an 85% efficiency for the battery, and to prolong its lifespan, the discharge depth is limited to 60% of its total capacity. The necessary battery capacity for the system was determined using the following formula:

$$capacity(Ah) = \frac{Total\ watt - hours\ per\ day\ consumed}{(0.85\ X\ 0.60\ X\ norminal\ battery\ voltage)} \quad (8)$$

Assuming the worst case of using 85% battery efficiency and 60% depth of discharge, as the total watt – hours per day required from the solar panel is 50MWWh, therefore the battery storage capacity was calculated as:

$$capacity(Ah) = \frac{50\ X\ 10^6}{(0.85X0.60X12)} = 816,9934.64Ah \quad (9)$$

An approximate value of **817,000Ah** was used as a safe margin. If a 250/48V battery is chosen with, the number of batteries that will be required will be

$$number\ of\ batteries = \frac{817,000Ah}{220Ah} = 3,713 \quad (10)$$

An approximate value of 3,715 unit of lithium-ion batteries were used with rated nominal voltage of 384volts 1300Kwh for this system design with all connections in parallel.

Inverter

The inverter transforms solar-generated DC power into usable AC power for electrical loads, with typical conversion efficiencies of 90-95% due to energy losses. For conservative estimates, we assume 90% efficiency and calculate required input power accordingly as calculated in [10].

$$Efficiency\ (\eta) = \frac{output\ power\ (to\ loads)}{input\ power\ (power\ from\ charge\ controller)} \quad (11)$$

From previous calculations, the total power to the load was given as 8.33Mw, thus the power from charge controller will be:

$$Input\ power\ (from\ charge\ controller) = \frac{output\ power\ (to\ load)}{Efficiency\ (\eta)} \quad (12)$$

Since the size ensure optimal performance, the inverter's rated power should exceed the load's wattage requirement by approximately 25–30% [10], thus a 9300MW inverter is required for design safety margin.

2.4 Hydrogen PEM Fuel Cell

This system directly converts hydrogen's chemical energy into DC electricity. A standard fuel cell system consists of three key parts: a fuel reformer for processing, the fuel cell stack itself, and a unit for power conditioning.

Employing Tafel's equation, which is expressed as in [6].
Where in the equations 13-,

$$V_{sack} = V_{open} - V_{ohmic} - V_{activation} - V_{concentration} \quad (13)$$

Where:

$$V_{open} = N_o(E^0 + E^1) \quad (14)$$

$$= N_o\left[\frac{-\Delta\bar{g}F^o}{2F} + \frac{RT}{2F}\ln\left(\frac{PH_2\sqrt{PO^2}}{PH_2O}\right)\right] \quad (15)$$

$$V_{ohmic} = (i + i_n)R_{FC} = I_{dc}R_{FC} \quad (16)$$

$$V_{activation} = N_o\frac{RT}{2 \propto F}\ln\left(\frac{I_{dc}}{I_o}\right) \quad (17)$$

$$V_{concentration} = Cln\left(1 - \frac{I_{dc}}{I_{\lim}}\right) \quad (18)$$

In the above equations,
N_o= Cell number
V_o= Open circuit voltage
R= Universal gas constant

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T= operating temperature of the fuel cell stack
F= Faraday's constant
PH_2= Partial pressure of Hydrogen
PH_2O= partial pressure of water
PO_2= Partial pressure of oxygen
PO= Standard reference pressure
∝= Charge transfer coefficient of the electrodes
I_{dc}= Operating current of the fuel stack
I_{lim}imiting current of the fuel cell stack

2.5. PEM Fuel Cell Design

Hydrogen stored in pressurized tanks serves as the primary fuel source for generating electricity through fuel cells. In this system, Proton Exchange Membrane (PEM) fuel cells were selected due to their compact design, operational simplicity, and low maintenance requirements. This fuel cell operates using ambient air as the oxidant, delivering DC power, water vapor, heat, and residual air as by products.

To meet the 100 MWh energy demand, multiple fuel cell modules are connected in parallel, with their combined output feeding into an inverter for power conditioning. The electrolyser will receive power from the batteries for a complete day, which is 24 hours; hence the power required from the fuel cell as depicted in [7];

$$power = \frac{Energy}{time} \quad (19)$$

$$Power = \frac{100\,X\,10^6}{24} = 4166666w \;\cong 4167kW \quad (20)$$

Given that the fuel cell used generates a DC power of 1.2kW, the number of fuel cell units required to generate 4.17Kw is:

$$number\ of\ units = \frac{4167kw}{1.2kw} = 3{,}472.5 \cong 3473$$

$$\approx 3473units\ \ will\ be\ combined\ into\ stacks\ and\ arrays\ \ for\ increased\ voltage\ and\ power\ output. \quad (21)$$

The number of fuel cell units used was 3473, as a safety margin. Therefore, the grid system will consist of an electrolyser that receive power from the batteries, which is connected to a deionized water and the hydrogen extracted is stored in the H tank and linked to 3473 units PEM FC.

2.6. Pumped-Storage Hydroelectricity (PSH)

$$e_v = \frac{E_t}{V_u} = \rho gh \quad (25)$$

The unit for energy density is

$$[e_v] = \frac{kg}{m^3}\frac{m}{s^2}m = \frac{kg.m^2}{s^2}\frac{1}{m^3} = \frac{J}{m^3} \quad (26)$$

The energy density is given by,

$$p = \rho gh \quad (27)$$

The unit is given by

$$[p] = \frac{kg}{m^3}\frac{m}{s^2}m = \frac{kg.m}{s^2}\frac{1}{m^2} = \frac{N}{m^2} = Pa \quad (28)$$

I_o= Exchange current density
C= Empirical coefficient for concentration losses

Using Equation 18, the steady-state voltage for a single cell ($N_o = 1$) and the corresponding power density versus current density can be derived. Unlike conventional power generation systems, fuel cells operate without moving parts or combustion, enabling near-perfect reliability (up to 99.99%) under ideal conditions.

Pumped-storage hydroelectric systems, alternatively referred to as pumped hydro energy storage (PHES), represent a grid-scale energy storage solution that utilizes water reservoirs at different elevations. This technology primarily serves to balance electrical grid demands by storing excess energy during low consumption periods and generating power during peak demand

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Principle of Operation of a Pumped-Storage Hydroelectricity (PSH)

Potential energy depicted with E is given by,

$$E = mgh \quad (22)$$

$$g = 9.8m/s^2$$

Pumped hydropower storage (PHS) is an energy storage system that operates by converting electrical energy into gravitational potential energy. The storage capacity depends on the water mass (m), gravitational acceleration (g), and hydraulic head height (h), following the fundamental energy equation E = mgh. Key components include paired reservoirs, pumps, turbines, and generators that facilitate this bidirectional energy conversion process

Assume $h \gg$ upper reservoir depth, h is constant both cycles. volume of water can be retained in the top reservoir, Vu

Equivalent energy stored in Top reservoir (assuming it is at a height *h*)

$$E_t = mgh = V_u\rho gh \quad (23)$$

Where $\rho = 1000\frac{kg^3}{m}$ the density of water, the units for this energy are given by [4]:

$$[E_t] = m^3\frac{kg}{m^3}\frac{m}{s^2}m = \frac{kg.m}{s^2}m = N.m = J \quad (24)$$

The energy density per unit volume of the stored water is therefore in [4,5]

Therefore, $\boldsymbol{p}$ is the energy density of the water turbine.

The transfer rate of energy to turbine from pump is given by

$$\boldsymbol{P} = e_vQ = pQ = \rho ghQ \quad (29)$$

Where **flow rate in volume of water is Q in [3]**

$$[P] = \frac{J}{m^3}\frac{m^3}{s} = \frac{J}{s} = W \quad (30)$$

Turbine total power.

$$P = VI \qquad (31)$$

. At large, in any energy system domain, **power is illustrated as product of driving force and flow**

$$P = e.f \qquad (32)$$

The overall energy capacity and deliverable power output are

$$E_t = V_u \rho g h \qquad (33)$$

$$P = \rho g h Q \qquad (34)$$

Pumped-storage hydroelectric systems, alternatively referred to as pumped hydro energy storage (PHES), represent a grid-scale energy storage solution that utilizes water reservoirs at different elevations. This technology primarily serves to balance electrical grid demands by storing excess energy during low consumption periods and generating power during peak demand.

The system's energy density varies linearly with the hydraulic head height [3]:

$$e_m = \frac{E_t}{m_u} = \frac{E_t}{V_u \rho} = \frac{V_u \rho g h}{V_u \rho} = gh \qquad (35)$$

Also, Available energy density shows a direct correlation with hydraulic head height

$$e_v = \frac{E_t}{V_u} = \rho g h \qquad (36)$$

Typical hydraulic heads for pumped-storage systems range from approximately 100 meters to one kilometre [2]

Calculation:

If for the system, we take the head, h, to be 300m [1]

Energy density for h=300m

$$\frac{e_v = \rho g h = 1000 \frac{kg}{m^3 . 9.81} m}{s^2 . 300m} = 2943000 J/m^3$$

$$= 2.9M J/m^3 \qquad (37)$$

Given that the complete revolution of a turbine is 3.6RPM, therefore

$$e_v = 2.9M \frac{J}{m^3} . \frac{1}{3600} \frac{Wh}{J} = 805 \frac{Wh}{m^3} \qquad (38)$$

Therefore

$$e_v = 805 \frac{Wh}{m^3} . \frac{1}{1000} \frac{m^3}{L} = 0.805 \frac{Wh}{L} \qquad (39)$$

L is litres.

Specific energy for h=300m

$$e_m = gh = 9.81 \frac{m}{s^2 . 300m} = 2943 \cong 2.9 \frac{kJ}{kg} \qquad (40)$$

Given that the complete revolution of a turbine is 3.60RPM [5], therefore

$$e_m = 2.9 \frac{kJ}{kg} . \frac{1}{3.6} \frac{Wh}{J} = 0.805 \frac{Wh}{kg} \qquad (41)$$

From the shared load, energy required from the PHES system is 50kWh, which can be taken as the stored energy. Therefore, the H_20 Volume required at top tank to drive turbine is

$$e_v = \frac{E_t}{V_u} \qquad (42)$$

$$V_u = \frac{E_t}{e_v} = 50X10^3 Wh . \frac{1}{0.805} \frac{Wh}{L} \qquad (43)$$

$$V_u = 50X10^3 Wh . 0.805 \frac{L}{Wh} = 40250L \qquad (44)$$

Hence, volume and speed of turbine are $V_u = 40250L \ and \ S = 3.6 \ RPM \ repectively$ ..

2.7. Mathematical Model of PHES Components

A standard pumped hydro energy storage (PHES) configuration includes two water reservoirs at different elevations, along with key components such as adjustable-speed pumps, hydraulic turbines, electrical generators, and connecting conduits. This section outlines the mathematical framework used to model the various elements of such a PHES installation.

Reservoirs

The PHES system consists of double elevation-separated reservoirs, operating in either open-loop (connected to natural water sources like rivers or lakes) or closed-loop (standalone, relying on artificial reservoirs and groundwater replenishment) configurations. While open-loop systems integrate with existing water bodies, systems in closed loop configuration are less common as most design are isolated. During energy storage, surplus renewable electricity pumps H_20 from the lower section to upper tank reservoir—modelled here as cubic structure, with hydropower capacity derived from its dimensional parameters (length, width, and height).

$$V_m = abh \qquad (45)$$

(V_u) can be expressed as:

$$V_u = V^i + Q_{nf} + Q_{\frac{T}{P}} \qquad (46)$$

The equation 46 accounts for the water volume retained in the reservoir from the preceding hour, along with the additional inflow from natural sources. The water flow term becomes positive during pumping mode (charging phase) and turns negative when the turbine operates (discharging phase). Among the loss mechanisms affecting reservoir water volume—assuming negligible seepage—evaporation represents a significant contributor. The quantity of water lost to evaporation can be determined using the referenced equation from [12].

$$V_{eva} = \frac{ET_0}{3.6X10^6} A \Delta t \qquad (47)$$

Where ET_0 represents the rate of reference evapotranspiration in millimetres per hour, A denotes the surface area of the reservoir (in square meters), and indicates the time interval in seconds. The reference evapotranspiration rate can be represented as in [13].:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \lambda \frac{37}{T_n + 273} U_{air}(e_0 - e_a)}{\Delta + \lambda(1 + 0.34U_{air})} \quad (48)$$

In this equation, Δ represents the slope of the saturation vapor pressure curve at a given temperature (kPa/°C), R_n is the net radiation (MJ/m²·h), G stands for the soil heat flux density (MJ/m²·h), λ is the psychrometric constant (kPa/°C), u_2 denotes wind speed measured at 2 meters above the reservoir surface (m/s), e_s refers to the saturation vapor pressure at ambient temperature (kPa), e_a is the average hourly actual vapor pressure (kPa), and T represents the hourly mean ambient temperature (°C)

$$V_{prep} = \frac{I}{3.6X10^6} A\Delta t \quad (49)$$

$$V_u = V^i + Q_{nf} + Q_{\frac{T}{P}} - V_{eva} + V_{prep} \quad (50)$$

2.8. Pipelines

This refers to the penstock. The system may utilize either elevated pipes or buried shafts and tunnel networks. The common diameter is usually 5-10m and one plant may have several penstocks. Typical flow velocities range between 1-5 m/s, allowing for a balance between cost and system efficiency at a specified flow rate (Q). Increased cross-sectional area results in reduced velocity, which decreases head loss but increases construction expenses [13]. The mathematical framework for pipeline analysis employs the following governing equations. The foundational principles for one-dimensional pipeline modelling are derived from the continuity and momentum conservation equations, typically expressed as in [14].

The variables in these equations represent the following parameters: Q denotes the mean flow rate through the pipe segment, h indicates the hydraulic head within the conduit, α represents the celerity of pressure waves, A corresponds to the pipe's flow area, θ signifies the pipeline's inclination angle relative to horizontal, f stands for the Darcy-Welsbach friction factor, and D designates the pipe's internal diameter y [14,15].

$$\frac{\partial h}{\partial x} + Q\frac{\partial Q}{\partial x} + \frac{\partial Q}{\partial t} + \frac{Q|Q|}{2D} r = 0 \quad \mathbf{(51)}$$

Hydraulic Machinery in PHS Systems

The turbine and adjustable-speed pump constitute critical elements in pumped hydro storage (PHS) system design. Proper component sizing requires careful consideration, as undersized equipment results in significant energy dissipation through head losses, while oversized units elevate capital expenditures and compromise operational efficiency. The mathematical representations for both the variable-speed pump and hydro turbine are presented subsequently in [15], the water volume transferred to the upper reservoir can be quantified by**:**

Where E_p The model determines the hourly power consumption (in kWh) required by the pumping system, which primarily utilizes excess energy generated from local renewable sources. This energy is used to pressurize and transport water to the elevated storage reservoir. The variable η represents the total operational efficiency of the variable-speed pump system. The parameters ρ, g, and H denote water density, gravitational acceleration, and net pumping head, respectively, while V signifies the pumped water volume.

During energy generation cycles, the amount of water released from the upper reservoir to the lower basin can be expressed as

Here, E_t (kWh) is energy realized hourly from turbine, while V_{dis} depicts volume of H_20 released. Q_T is the water turbine through put, and η_T is the efficiency of the turbine used [15]?

$$E_p = \min\left(\frac{V_m - V^i}{3600} . V_p\right) \frac{\rho g}{\eta_p} \left(\frac{V^i}{ab} + h^i\right) \quad (52)$$

$$Q_{pump} = \frac{\eta_{pump} E_p}{\rho g \left(\frac{V^i}{ab} + h^i\right)} \quad (53)$$

2.9. Generator/Motor

The generator's rotational behaviour is modelled using a first-order swing equation. This analysis examines three distinct operational scenarios: energy storage (charging) periods, power generation (discharging) phases, and complete charge-discharge cycles, as investigated by [16]. For the case of operating with constant rotation speed, the following equation should be formulated as in [16]:

$$\mathrm{J}\frac{\pi}{30}\frac{\mathrm{dn}}{\mathrm{dt}} = \mathrm{M_t} - \mathrm{M_g} - \frac{30\mathrm{e_g P_r}}{\mathrm{n_r^2}\pi}\Delta\mathrm{n} \quad (54)$$

For mode where rotation speed is constant, the equation is given by:

$$\mathrm{n} = \mathrm{n_c}(\mathrm{f_g} = \mathrm{f_c}) \quad (55)$$

$\mathrm{M_g}$ and $\mathrm{e_g}$ A zero parameter value indicates is landed (offgrid)operation, with the system behavior described by the following governing equation:

$$\mathrm{J}\frac{\pi}{30}\frac{\mathrm{dn}}{\mathrm{dt}} = \mathrm{M_t} \quad (56)$$

In the preceding equations $\mathrm{J, n, M_t, M_g, e_g, P_r, n_r, n_c, f_g}$, and $\mathrm{f_c}$ represent, in order: the system's moment of inertia, angular velocity, mechanical torque from the turbine, resistive torque from the generator, load damping coefficient, nominal power rating, rated angular velocity, specified rotational speed, electrical frequency output, and reference frequency.

2.10. PHES Efficiency

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Round-trip efficiency (System efficiency)

$$\eta_{rt} = \frac{E_{out}}{E_{in}} 100\% \qquad (57)$$

Where, during energy storage operations, E_n represents the grid-supplied electrical power input to the pumping facility

Efficiency of the pumping operation is given as

$$\eta_p = \frac{E_s}{E_{in}.100}\% \qquad (58)$$

Where E_s is in joule depicts stored energy.
Stand point energy of the volume of H_2O, V_u, pumped to the upper reservoir

$$E_s = V_u \rho g h \qquad (59)$$

E_{in} denotes the grid-supplied electricity consumed during water pumping operations. This electrical energy is converted to hydraulic work input at

$$E_{in,pump} = E_{in}.\eta_{trans}.\eta_{motor} \qquad (60)$$

Where
η_{trans} and η_{motor} depicts efficiencies of the rotating machines.
The volume is given by [13]

$$V_u = \frac{E_{in,pump}}{\rho g h}.\eta_{pump}.\eta_{pipe.p} \qquad (61)$$

Where
η_{pump} is the pump efficiency
$\eta_{pipe,p}$ is the efficiency of penstock in pumping condition.
total volume of pumped H_20 as shown in [15]

$$V_u = \frac{E_{in}}{\rho g h}.\eta_{trans}.\eta_{motor}.\eta_{pump}.\eta_{pipe.p} \qquad (62)$$

Thus, the **net energy conversion efficiency** for the full charge-discharge cycle equals [16]

$$\eta_{rt} = \frac{E_{out}}{E_{in}} = \eta_p.\eta_g \qquad (63)$$

$$\eta_{rt} = \eta_{trans}.\eta_{pump}.\eta_{pipe,p}.\eta_{pipe,g}.\eta_t.\eta_{gen}.\eta_{motor} \qquad (64)$$

Calculation:
Assume efficiency of the system to be designed, $\eta_{rt} =$ 80%
Size of pump P in KW,
$P = \frac{\rho.g.Q.H}{1000}$ where P is power required in KW, ρ is density of water 1000 kg/m2, g is acceleration due to gravity 9.81m/s^2, Q =flow rate in m^3/s.
Since, Flow rate Q=50 L/S =0.05m^3/S height=300m.

$$P = \frac{1000 \text{ x } 9.81 \text{ x } 0.05 \text{ x } 300}{1000} = 147.15 \text{ KW} \qquad (65)$$

If the pump efficiency is 80%

$$P_{input} = \frac{\text{Phydraulic}}{\text{Efficiency}} = \frac{147.15}{0.80} = 183.94\text{KW}$$

Total Time Required for Pumping; Total volume of water 40250L=40.25m^3
Time(hours)

$$= \frac{V}{Q\text{x } 3600} = \frac{40.25}{0.05 \text{ x } 3600} = 0.2236\text{hrs} \qquad (66)$$

Therefore, during energy storage operations, the electrical power consumption from the grid amounts to

$$E_{in} = 147.15\text{kW X } 0.2236 \text{ X } \frac{1}{0.8} = 41.128\text{KWh} \qquad (67)$$

Hence 41.128KWh is required for pumping.

Assuming the surface area for the penstock used in this design is flat, the volumetric flow rate is given by

$$Q = V.A \qquad (68)$$

Where
V = flow velocity and A = cross-sectional area

2.11. PHES Pumping and Generation Durations

As a result of inherent system losses, the time required for energy storage (charging) and electricity generation (discharging) varies significantly—even when power input and output capacities are matched. Consequently [15]

Charging (pumping) time:

$$t_p = \frac{E_{in}}{P_{in}} = \frac{E_s}{\eta_p P_{in}} \qquad (69)$$

$$t_p = \frac{V_u \rho g h}{\eta_p P_{in}} \qquad (70)$$

Discharging (generating) time:

$$t_g = \frac{E_{out}}{P_{out}} = \frac{E_s \eta_g}{P_{out}} \qquad (71)$$

$$t_g = \frac{V_u \rho g h \eta_g}{P_{out}} \qquad (72)$$

The energy recovery time proportion:

$$\frac{t_g}{t_p} = \frac{V_u \rho g h \eta_g}{P_{out}} \frac{\eta_p P_{in}}{V_u \rho g h} = \frac{P_{in}}{P_{out}} \eta_g \eta_p \qquad (73)$$

$$\frac{t_g}{t_p} = \frac{P_{in}}{P_{out}} \eta_{rt} \qquad (74)$$

Under conditions of balanced charging and discharging power;

$$\frac{t_g}{t_p} = \eta_{rt} \qquad (75)$$

Accordingly, the generation-to-pumping time proportion matches the facility's round-trip energy conversion rate.

3.0 RESULTS AND DISCUSSION

The reason for the different renewable energy sources is the fact that the different weather conditions experienced in this zone affects the renewable energy available. The major renewable energy sources being considered in this study is the photovoltaic solar cells which depends on sunlight and the pumped hydro storage which depends on rainfall.

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The photovoltaic cells will generate its maximum output when the sunlight is at its peak. It is seen that in Ekpoma, the highest sunlight is experience between the month of November and May, with November, December, January and February having the overall highest sunlight. It therefore signifies that the photovoltaic solar cells will produce maximally between November and May. During times of low sunlight and high rainfall as seen from figure.2, the Pumped hydro storage will generate maximally. From the chat this will be between the month of April and October, with June, July, August and September having the highest rain fall.

The Fuel cell requires power from the Photovoltaic system or the Pumped-Storage Hydroelectricity to carry out electrolysis after which power can be generated. Hence the fuel cell will be used to compensate for power efficiency when either the Photovoltaic system or the PSH system has a low output when sunlight and rainfall are not at their peaks such as in March, April, May and October

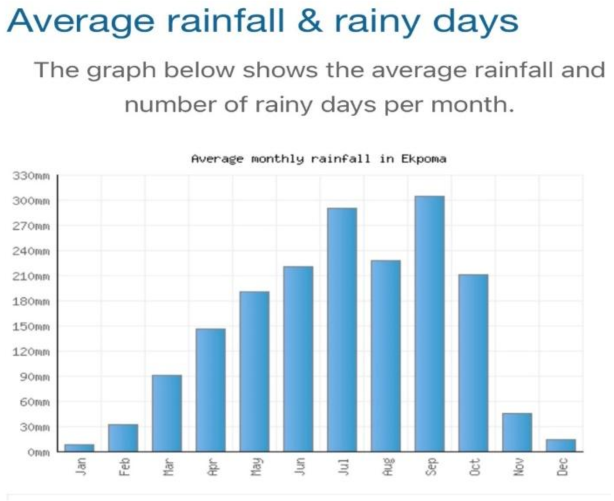


Figure 2.: Chart showing Annual rainfall in Ekpoma

To evaluate the design, know it was simulated using a HOMER PRO software. This part of the research presents the data output collected based on location of design and compares different simulated result based on the suggestion of the software and each components specification

3.1 Simulation

The simulation process started by deciding the location where the design will be implemented and after specifying the location, different data regarding our location were obtained.

Figure 3. Aerial view of the location, Ambrose Alli University Ekpoma, Nigeria,(310103, 6^{0}44.3’N, 6^{0}4.9’E)

The electric load was then specified as commercial load and the software after downloading data online showed the total specified energy that is required by commercial loads. The software allowed for the input of the system required energy, which based on our assumption was specified. Upon incorporating the PV array, the modelling platform acquired 264 months of historical solar resource data (July 1983-June 2005) from NASA's Surface Meteorology and Solar Energy repository systematically, reviewed in 2025 under current cost and economic factors, with monthly mean global horizontal irradiance metrics displayed in the result.

Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.598	5.560
Feb	0.568	5.600
Mar	0.521	5.390
Apr	0.494	5.160
May	0.476	4.860
Jun	0.445	4.440
Jul	0.392	3.940
Aug	0.371	3.820
Sep	0.391	4.040
Oct	0.452	4.500
Nov	0.539	5.060
Dec	0.586	5.320

Downloaded at 8/20/2022 1:41:40 AM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: 6.75
cellMidpointLongitude: 6.25

Annual Average (kWh/m²/day): 4.81

Scaled Annual Average (kWh/m²/da 4.81

Figure 4.: Solar radiation data obtained from NASA by HOMER Pro software for a 22yrs period

The other systems created where specified and added which include the converter, battery storage, micro grid controller, electrolyser, hydrogen tank and fuel cell generator. There was problem in adding the pumped hydro storage to the design because; the software did not have a generic PHS system; hence a PHS system can only be specified by using a storage system such as a battery. Hence an already made PHS battery storage was used to represent the PHS. The PHS system could not be added by using a micro-hydro plant, because, according to the data obtained by the software from NASA about the geography

of the area, there was no recognized large body of water available in Ekpoma.
From the above problems encountered, we resolved in creating two combined system;

Three different simulations were carried out, which are:

(a) PV-FC design using 384V DC batteries based on our calculation

(b) PV-FC design using 192V DC batteries based on the software recommendation

(c) PHS-FC-PV design using 384V DC batteries the results for each simulation are shown below.

3.2 PV-FC Design Simulation Result using 192V DC Batteries

After simulation, PV-FC-192V model, the following result was obtained for the system as presented:
converter.
PV array power output:
The simulation was done for a year, hence the rated capacity for the year for the PV array is 161MW with a mean output of 26MW, the minimum power output per day zero (0) and the maximum power output per day, 157kW. The total power output for the year is 227,864mWh. It can also be seen that the PV array functions effectively between the 6th hour to the 18th hour, and the output power varies between 32MW and 160MW at different time and period of the year. Between the hours of 0 to 6 and 18 to 24, the output power from the array is zero (0).
Inverter output power for FC-PV-384V battery:
The inverter has a capacity of 26.6MW and the mean output is 6.25MW compared to our calculated 8.33MW from the previous chapter. Similar to the PV array the inverter only output effective power between the 6th to 18th hours of the day, while output power during the hours of 0 to 6 and 18 to 24 are between 0 to 5Mw.

Battery charging for FC-PV-48V battery:
The charging state of the batteries, showing that the batteries will be 100% charged between the hours of 6 and 18, while at other time of the day, the state of charge will be 52% to 88%. The state of charge will be 40% to 52% at certain time of the day.
Hence from the result the least state of charge is 40%.
Hydrogen stored in the tank and the power utilized by the electrolyser to supply hydrogen for a year: The hydrogen stored is highest (60kg to 80kg) at midyear but the power utilized by the electrolyser is less at midyear because the power supplied by the PV array reduces during the raining season.

Electrolyser input power for FC-PV-384Vbattery:
The rated capacity of the electrolyser is 4.3MW, while the electrolyser receives power between the hours of 6 to 18 per day all through the year with the highest input power being 4.3MW. The mean input to the electrolyser is 1.6MW, having a minimum output of zero (0), and a maximum output power of 4.3Mw. The mean output hydrogen is 0.0348kg/hr with a minimum output of zero (0) and a maximum hydrogen output of 0.0927kg/hr. The total hydrogen produced all through the year is 305kg/yr.

Fuel consumption for the FC-PV-384V battery:
It is seen that the fuel (stored hydrogen) consumption is low although it is distributed all through the year, Operational data indicates yearly hydrogen consumption of 296 kg, equating to daily and hourly averages of 811 g and 33.8 g respectively

Fuel cell generator output for the FC-PV-384V battery:
With the total hours of operation being 327hrs/year, having a total electric production of 2,315MW/year with a mean output of
7.08kW. The total number of times the fuel cell will be required is 227starts/year.

PV-FC Design Simulation Result using 192V DC Batteries
After simulation, the following result was obtained for the system:
Cost summary FC-PV-192V battery:
The PV arrays incurred the highest cost, followed by the fuel cell generator and the converter.
PV array power output:
The rated capacity for the year for the PV array is 58.8MW with a mean output of 9MW, the minimum power output per day zero (0) and the maximum power output per day, 57.5MW. The total power output for the year is 83,389MWh only. It can also be seen that the PV array functions effectively between the 6th hour to the 18th hour, and the output power varies between 12MW and 60MW at different time and period of the year.

Inverter output power for FC-PV-12V battery:
the inverter has a capacity of 20.8MW and the mean output is 6.25MW similar to the FC-PV batteries with 384v rating. Similar to the PV array the inverter only output effective power between the 6th to 18th hours of the day, while output power during the hours of 0 to 6 and 18 to 24 are between 0 to 5MW.

Battery charging for FC-PV-12V battery:
The result shows the charging state of the batteries, showing that the batteries are barely able to maintain 100% charge; rather they fall between 78% and 88%. During some days of the year, the batteries are between 40% and 64%
.
Hydrogen stored in the tank and the power utilized by the electrolyser to supply hydrogen for a year:

The hydrogen stored is highest (80kg) at midyear but the power utilized by the electrolyser is much lesser than the 48v batteries, at midyear because the power supplied by the PV array reduces during the raining season.

Electrolyser input power for FC-PV-192V battery;
The rated capacity of the electrolyser is 4.3MW. The electrolyser receives power between the hours of 8 to 18 per day which is not constant all through the year as compared to the 384v battery system. The highest input power being 4.3Mw, the mean input to the electrolyser is 0.5925KW, having a minimum output of zero (0), and a maximum output power of 4.3MW. The mean output hydrogen is 0.0128kg/hr with a minimum output of zero (0) and a maximum hydrogen output of 0.0927kg/hr. The total hydrogen produced all through the year is 112kg/yr.

Fuel consumption for the FC-PV-12V battery:
It is seen that the fuel (stored hydrogen) consumption is very low and it is not
distributed all through the year, The PEM fuel cell exhibits an 84.5 kg·yr⁻¹ consumption rate, corresponding to mass-flow rates of 231 g·day⁻¹ and 9.64 g·hr⁻¹.

Generator output for the FC-PV-192V battery:
For the total hours of operation being 88.0hrs/year, having a total electric production of 692MWh/year with a mean output of 7.86MW. The total number of times the fuel cell will be required is
40.0starts/year.
Therefore, it can be concluded that the PV-FC-384v system is much more efficient compared to the PV-FC-192v. Hence the initial design in previous chapter has been proven to be the most efficient.

3.4 PSH-PV-FC Design Simulation Result using 384V DC Batteries

The generic pumped hydro of the HOMER PRO software. The simulation models a reservoir with 1 million cubic meters (1000 × 10³ m³) of storage capacity, designed for controlled release over 12-hour generation cycles. Given a 100-meter hydraulic head and 90% turbine-generator efficiency, the system's power output and energy production during discharge are computed using these equations:

Discharge:

$$\text{rate flow is} = \frac{1000x10'3\ m^2}{(384X60X60)s} = \frac{0.723m^2}{s} \qquad (74)$$

The energy produced at 90% η= (H20 in gram) (g. constant) (head height) (flow rate) (gen. efficiency)

The power generated at 90% η

$$= 1000x10'3\ \ x\ 9.81\ X\ 1000x\ 0.000231\ X\ 0.90 \cong 2039kW\ x\ 0.90 = 1.835549MW \qquad (75)$$

Energy produced within a 12 hours duration = 1.835549 MW x 12hours = 22.026MWh

Charging:

Assuming when functioning in reverse pumping mode at equivalent power levels, the hydraulic system requires a flow rate calculable at 90% energy conversion efficiency through, which is:

$$= \frac{20.4375MW\ X\ 0.9}{9.81\ X\ 100} = \frac{0.01875m^2}{s} \qquad (76)$$

Required duration for reservoir to get filled is

$$= \frac{1000m^2}{flowrate} X\ \ 3600 = 14.8hours$$

The electrical energy is 1.835549MW x 14.8hours = 27.166MWh

For PHS systems, the complete cycle efficiency represents the percentage of charging energy that is successfully recovered during generation operations. That is:

$$= \frac{22.026}{27.166} = 0.81 \qquad (77)$$

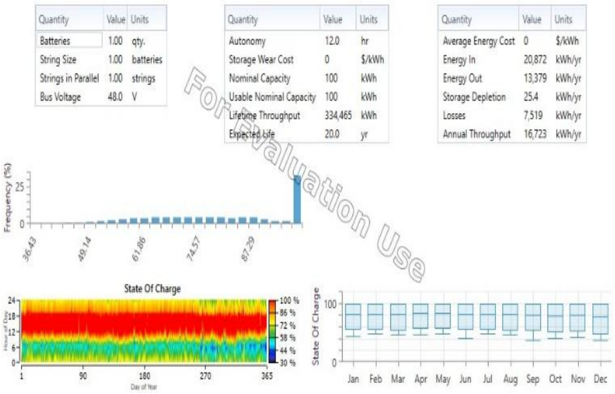
Using similar generator to turbine act as pumping reserve, the peak discharge and charge current remains the constant.

The analysis assumes a 22 MW generation unit. The peak capacity is determined by dividing the rated power output by the system's nominal voltage:

$$= \frac{22.026\ X\ 1000x10'3}{240} = 91{,}775Ah \qquad (78)$$

Total cost implication for the system
The cost summary of the design and from the result, the PV array has the highest cost and it is followed by the generic pumped hydro, before the fuel cell and the system converter.

PV array power output:
The simulation was done for a year, hence the rated capacity for the year for the PV array is 500MW with a mean output of 81MW, the minimum power output per day zero (0) and the maximum power output per day, 489MW. The total power output for the year is 709, 399mwh. It can also be seen that the PV array functions effectively between the 6th hour to the 18th hour, and the output power varies between 100mW and 500mW at different time and period of the year. Between the hours of 0 to 6 and 18 to 24, the output power from the array is zero (0).



Quantity	Value	Units
Batteries	1.00	qty.
String Size	1.00	batteries
Strings in Parallel	1.00	strings
Bus Voltage	48.0	V

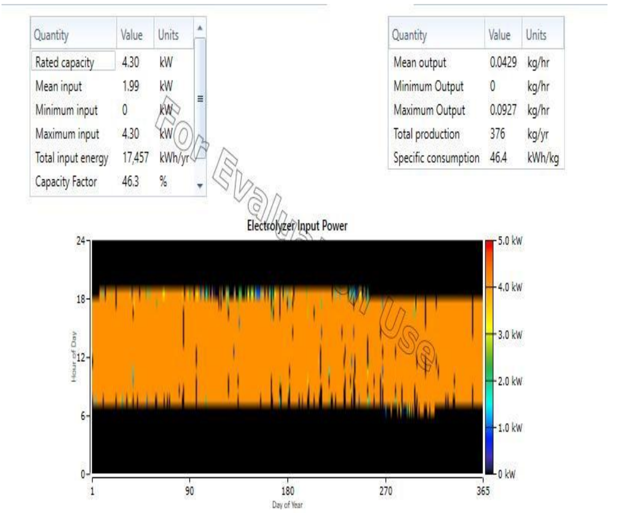
Quantity	Value	Units
Autonomy	12.0	hr
Storage Wear Cost	0	$/kWh
Nominal Capacity	100	kWh
Usable Nominal Capacity	100	kWh
Lifetime Throughput	334,465	kWh
Expected Life	20.0	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	20,872	kWh/yr
Energy Out	13,379	kWh/yr
Storage Depletion	25.4	kWh/yr
Losses	7,519	kWh/yr
Annual Throughput	16,723	kWh/yr

Figure 5: Battery charging for PSH-PV-FC design

The result shows (figure 5) the charging state of the batteries. The batteries will be 100% charged between the hours of 6 and 18 and sometimes to 24, while at other time of the day, the state of charge will be 58% to 86%. The state of charge will be 40% to 58% at certain time of the day of the year. Hence from the result the least state of charge is 40%.

Further, the hydrogen stored is (0kg to 16kg) towards the end of the year and the power utilized by the electrolyser is equal all through the year, because the power supplied is not only from the PV array but also from the PSH system.

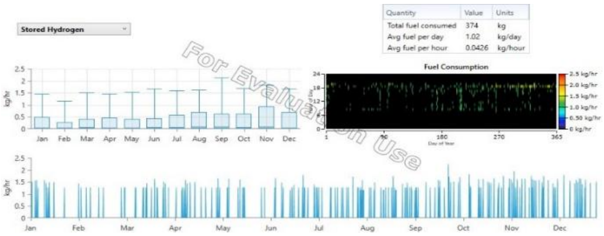


Quantity	Value	Units
Rated capacity	4.30	kW
Mean input	1.99	kW
Minimum input	0	kW
Maximum input	4.30	kW
Total input energy	17,457	kWh/yr
Capacity Factor	46.3	%

Quantity	Value	Units
Mean output	0.0429	kg/hr
Minimum Output	0	kg/hr
Maximum Output	0.0927	kg/hr
Total production	376	kg/yr
Specific consumption	46.4	kWh/kg

Figure 6: Electrolyser input power for PSH-FC-PV

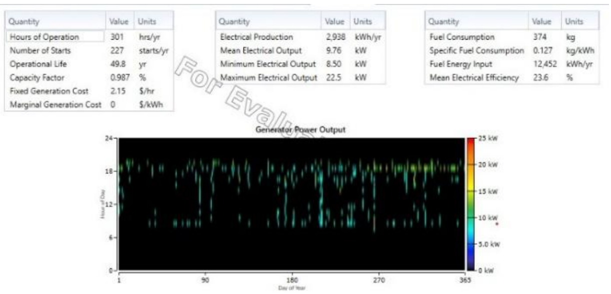
From figure 6, the rated capacity of the electrolyser is 4.3MW, while the electrolyser receives power between the hours of 6 to 18 per day all through the year with the highest input power being 4.3Mw. The mean input to the electrolyser is 1.99kW, having a minimum output of zero (0), and a maximum output power of 4.3MW. The mean output hydrogen is 0.0429kg/hr with a minimum output of zero (0) and a maximum hydrogen output of 0.0927kg/hr. The total hydrogen produced all through the year is 376kg/yr.



Quantity	Value	Units
Total fuel consumed	374	kg
Avg fuel per day	1.02	kg/day
Avg fuel per hour	0.0426	kg/hour

Figure 7: fuel consumption for the PSH-FC-PV

From the above result (figure 34), it is seen that the fuel (stored hydrogen) consumption is distributed all through the year, Operational data indicates the fuel cell requires 374 kg of hydrogen annually, equating to daily and hourly consumption rates of 1.02 kg and 42.6 g respectively.



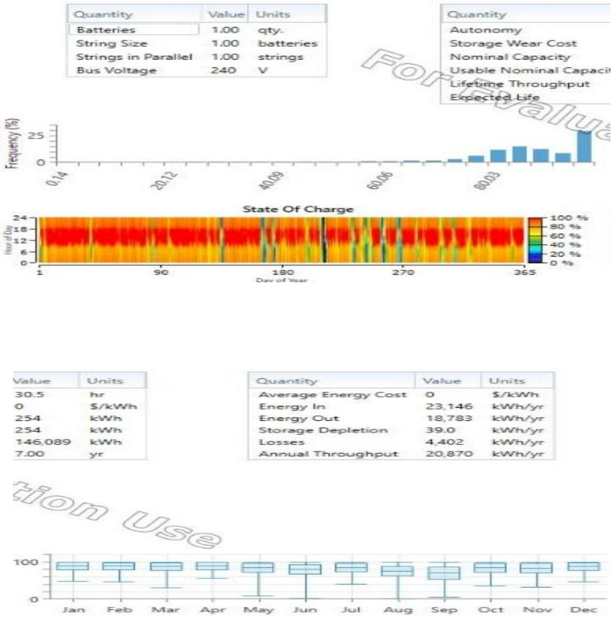
Quantity	Value	Units
Hours of Operation	301	hrs/yr
Number of Starts	227	starts/yr
Operational Life	49.8	yr
Capacity Factor	0.987	%
Fixed Generation Cost	2.15	$/hr
Marginal Generation Cost	0	$/kWh

Quantity	Value	Units
Electrical Production	2,938	kWh/yr
Mean Electrical Output	9.76	kW
Minimum Electrical Output	8.50	kW
Maximum Electrical Output	22.5	kW

Quantity	Value	Units
Fuel Consumption	374	kg
Specific Fuel Consumption	0.127	kg/kWh
Fuel Energy Input	12,452	kWh/yr
Mean Electrical Efficiency	23.6	%

Figure 8: Generator output for the PSH-FC-PV-48V battery

From the result above (figure 35), the graph shown is similar to that of figure 4.28, with the total hours of operation being 301hrs/year, having a total electric production of 2938MWh/year with a mean output of 9.76MW. The total number of times the fuel cell will be required is 227starts/year.



Quantity	Value	Units
Batteries	1.00	qty.
String Size	1.00	batteries
Strings in Parallel	1.00	strings
Bus Voltage	240	V

Quantity	Value	Units
Autonomy	30.5	hr
Storage Wear Cost	0	$/kWh
Nominal Capacity	254	kWh
Usable Nominal Capaci	254	kWh
Lifetime Throughput	146,089	kWh
Expected Life	7.00	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	23,146	kWh/yr
Energy Out	18,783	kWh/yr
Storage Depletion	39.0	kWh/yr
Losses	4,402	kWh/yr
Annual Throughput	20,870	kWh/yr

Figure 9: Pumped-Storage Hydroelectricity

The result shows (figure 9) the state of the PHS system. The PSH state will be 100% between the hours of 6 and 18 (that is the 12hours during discharge and generation), while at other time of the day, the state of the PSH system will be 80%. The state of charge will be 0% to 60% at certain time of the day (that is during charging).

Table.1 shows the results obtained from the simulations for the following: cost summary, PV power output, inverter output, battery and PHS output, hydrogen and electrolyser output, fuel consumption, and fuel cell generator output. Using this table, comparison was made among the PV-FC-384V battery design model, PV-FC-192V battery design model and PHS-PV-FC-384V battery design model.

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For the cost summary, the following lifetimes where assumed: the PV system exhibits life span of 25 years, the inverter and also the electrolyser had a working duration of 15 years, fuel cell generator had a lifetime of 1 year and 7 months, the 48V batteries had a lifetime of 20 years and the pumped hydro storage had a life time of 7 years

Table 1: Analysis of Result

SYSTEM COST SUMMARY ($1=NGR1600	**PV-FC-384 BATTERIE**	**PV-FC-192 BATTERI S**	**PSH-PV-FC SYSTEM**	**PSH SYSTE**
Capital	NGR 168,894,216 00	NGR 68,417,480, 00	NGR 146,545,416 00	
Replacement	NGR 1,353,688,00	NGR 2,937,552,0 0	NGR 1,653,104,00	
Operating a Maintenance	NGR 9, 57 164,000	NGR 4,298,776 ,000	NGR 17,726,972,0 0	
Total	NGR 179,025,896 00	NGR 74,177,764, 00	NGR 164,420,128 00	
PV POWE YIELD				
Capacity	165MW	68.5MW	325MW	
Mean yield	23.3Mw	9.52Mw	81.0Mw	
Minimum Yiel	0	0	0	
Peak Output	155Mw	57.7Mw	289kw	
Total output	227,864Mw yr.	83,369Mwh r.	709,399Mw yr.	
Output variatio	32Mw-160Mw	12Mw-60M	50Mw-250Mw	
INVERTER YIELD				
Capacity	26.6Mw	20.8Mw	31.5Mw	
Mean yield	6.25Mw	6.25Mw	8.33Mw	
Minimum outp	0	0	0.119kw	
Peak output	21.5kw	20.8kw	28.7kw	
Losses	2,881Mwh/y	2,881Mwh/ .	3,842Mwh/y	
BATTERY C PSH				
6-18 hours	100%	78%-88%	100%	100%
Other times	52%-88%	40%-88%	58%-88%	80%
Certain time	40%-52%	40%	40%-58%	0-60%
HYDROGEN				
Storage highes	80kg	80kg	80kg	
ELECTROLY ER				
Capacity	4.3Mw	4.3Mw	4.3Mw	
Mean input	1.6Mw	0.592Mw	1.99Mw	
Minimum outp	0	0	0	
Maximum outp	4.3Mw	4.3Mw	4.30Mw	
Mean hydrog output	0.0345kg/hr	0.0128kg/h	0.0429kg/hr	
Lowest hydrog output	0	0	0	
Peak hydrog yield	0.0927kg/hr	0.0927kg/h	0.0927kg/hr	
Hydrogen produced all ye	305kg/yr.	112kg/yr.	376kg/yr.	
FUEL CONSUMPTI N				
Fuel c consumption (total)	296kg/yr.	84.5kg/yr.	374kg/yr.	
Fuel c consumption (day)	0.811kg/day	0.231kg/da	1.02kg/day	
Fuel c consumption (hour)	0.0338kg/hr	0.00964kg/	0.0426kg/hr	
FUEL CE L GENERATO OUTPUT				
Hours operation	327hrs/yr.	88.0hrs/yr.	301hrs/yr.	
Total elect production	2,315Mwh/y	692Mwh/yr	2,938Mwh/h	
Mean output	7.08Mw	7.86Mw	9.76Mw	
Minimum electric output	6.08Mw	6.25Mw	8.50Mw	
Maximum electric output	17.5Mw	15.6Mw	22.5Mw	
Starts	227starts/yr.	40starts/yr.	227starts/yr.	

Based on the design and simulation, the following key findings were observed: The PV-FC-384V battery design incurred the highest overall cost compared to the PV-FC-192V battery and the PSH-PV-FC system, though the latter had the highest operating and maintenance expenses. The PSH-PV-EC system delivered the highest total output power but exhibited the greatest variation during active hours. Meanwhile, the PSH-PV-FC system demonstrated superior performance in several aspects, including the highest inverter mean output, longest periods of 100% charged batteries, and the most consistent water pumping levels (either 100% or 80% reservoir capacity). Additionally, its electrolyser achieved the highest mean input power and hydrogen output, producing the largest annual hydrogen quantity. This design also consumed the most hydrogen, correlating with its elevated electricity production. While the PV-FC-384V battery design had the longest fuel cell operating hours, the PSH-PV-FC system outperformed it in total electric production, mean power output, and peak performance metrics, despite both systems utilizing the fuel cell an equal number of times annually. In contrast, the PV-FC-192V battery design consistently ranked lowest across all evaluated variables.

4.0 Conclusion

This study focused on using renewable energy for the implementation for an integrated grid-tied renewable energy system combining solar PV, hydroelectric, and fuel cell technologies with battery and Pumped-Storage Hydroelectricity (PSH) system towards energy harvesting in university campuses; so as to mitigate the lingering electricity issues. Simulation output shows the integrated grid-tied renewable energy system combining solar PV, hydroelectric /FC hybrid with battery and PHS storage system; after comparison was made between the PV-FC-192V battery design, PV-FC-384V battery design and PSH-FC-PV system design, it can therefore be concluded that the PSH-PV-FC grid hybrid design, despite its high operating and maintenance cost, is the most efficient.

Conflict of Interest

From conception to realization of the research paper, no conflict of exist between the authors.

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Authors' Contribution

Emmanuel Esekhaigbe conceived the research idea, developed the experimental design, and supervised the entire project. Ogheneale Orie conducted the laboratory experiments, analyzed the data, and contribute.

Author's Declaration

The authors affirm that the content of this manuscript is original and is not been considered in any other journal. The authors accept full responsibility for the integrity and accuracy of all data and interpretations presented herein

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