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Feasibility Study of Small hydropower based Off-Grid Hybrid Power System for Rural Electrification of Selected Communities in Southwest, Nigeria

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Abstract: *Electricity supply in Nigeria is insufficient, unreliable and absolutely unsustainable. Most of the rural communities in the Southwestern states of Nigeria are not connected to the grid, even though there are abundant renewable energy resources (RES) that can easily be harnessed to bridge the wide supply-demand energy deficit. RES alone, due to its stochastic nature, cannot be reliable, hence the need to combine two or more RES (with conventional energy sources) to form a hybrid system that are complementary in nature. This work examined the techno-economic viability of off-grid Small Hydro-Solar PV-Diesel Hybrid Power System (HPS) with battery storage in two selected villages in Southwest States of Nigeria. The hydro and solar resources for the study areas (Itapaji in Ekiti State and Owena in Ondo State) covering a period of twenty five years were used for the study. The data collected were analyzed and used as inputs into HOMER software. The results showed that the most suitable hybrid configuration for Itapaji and Owena was Solar PV-Battery-Small hydropower. The Cost of Energy (COE) in Itapaji and Owena were $0.210/kWh and $0.255/kWh respectively. The Net Present Cost (NPC) and COE for the entire system architecture suggested for the two study areas are within acceptable standard and are emission free. The economic metrics also showed high investment attraction for hybrid projects.*

Keywords**:** *Off-grid, rural electrification, small hydro, solar PV, southwestern states, viability study.*

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I. Introduction

Sustainable energy is vital to the socioeconomic development of any nation [1].The provision of quality health care; social infrastructure and human development require adequate, affordable and sustainable electric power. Most villages and communities in Nigeria have no access to electric power utility, partly owing to the terrain and topography of the zones or gross power inadequacies [2]. Some of these areas are either too far away from the grid or are sparsely populated so that extending the national grid to these areas is unrealistic and not economically viable compared to using renewable energy technology as an alternative [3]. Rural dwellers in the Southwest zone have been the worse receiver of the brunt power shortages. Many have resulted to the use of kerosene lamps, solid fuel for cooking, petrol and diesel generators, with its attendant negative environmental impacts such as air and noise pollution and other health hazard effects [4].

Presently, there is a global quest for renewable energy within the framework of clean development mechanism (CDM) which is set to abate the effects of ozone layer depletion and global warming [1-11]. It is safe, abundant and clean to use when compared to fossil fuels. Ensuring continuity, availability and reliability of power supply in rural communities require an integration of different renewable energy resources as a better option to meet the energy challenge than a single system [10]. Hence, the need for a hybrid energy system comprising two or more renewable energy sources (RES) to augment supply from the conventional source that is only sufficient for base use in complementary manner.

Researchers have shown the energy potentials and sustainability of a hybrid power system of RES with a convectional source in different parts of the world and in Nigeria are effective [2-14]. Some have proposed certain hybrid technologies suitable for rural areas based on the available RES [5-14]. Adebanji et al [1] developed an optimal sizing algorithm for a distant village in Nigeria using Genetic Algorithm (GA). The hybrid system consists of small hydro, PV, diesel and battery system. Vendoti et al [11] carried out a feasibility study of electrifying three villages in Kollegal, India using Genetic Algorithm (GA) and HOMER promo software. A comparative analysis of the two results showed that GA hybrid combination is better than that of HOMER software. The optimal hybrid combination consists of biogas, biomass, solar, wind, fuel cell and battery.

Olatomiwa et al [12] conducted a feasibility study of a hybrid system consisting of PV, diesel, wind and battery system. A comparative study of the two optimal configurations was made. Khan et al [13] implemented a grid connected PV-battery system for a campus in Malaysia. The basic goal of the research is to meet up with the load demand and reduces total dependence on the national grid. Research into off-grid hybrid system incorporating Small Hydro, solar PV, Diesel Generator and battery storage in single topology in Southwest states of Nigeria at the moment is scarcely available [1, 4-16]. Most publications on hybrid renewable energy study in Southwest states of Nigeria did not include SHP hybrid configuration in their research work despite its availability. Unlike previous research works, this study focuses on the feasibility study and techno economic evaluation of an off-grid small hydro-photovoltaic-diesel generator-battery bank hybrid system in single topology with SHP being the base energy source. The research work covers two choice communities, Itapaji and Owena, in Southwest states of Nigeria. The HPS components consist of SHP, PV, DG, BATT and other accessories.

II. Material And Methods

Data Acquisition: The load demand of the two study areas were obtained through the use of questionnaires and from Benin Electricity Distribution Company (BEDC), Nigeria. The hydro resource data of the areas such as stream hydrograph were obtained from Benin-Owena River Basin Development Authority (BORBDA), Benin City [17]. The daily solar radiation data and clearness indices of the study areas covering a period of twenty five years for the two study areas were obtained from NASA's global satellite database [18].

Description of the Study Areas: This work uses Itapaji in Ekiti state and Owena in Ondo state, (Figure 1) both in Southwest zone as case studies. These states have natural renewable energy resources that can be harnessed for electricity generation.

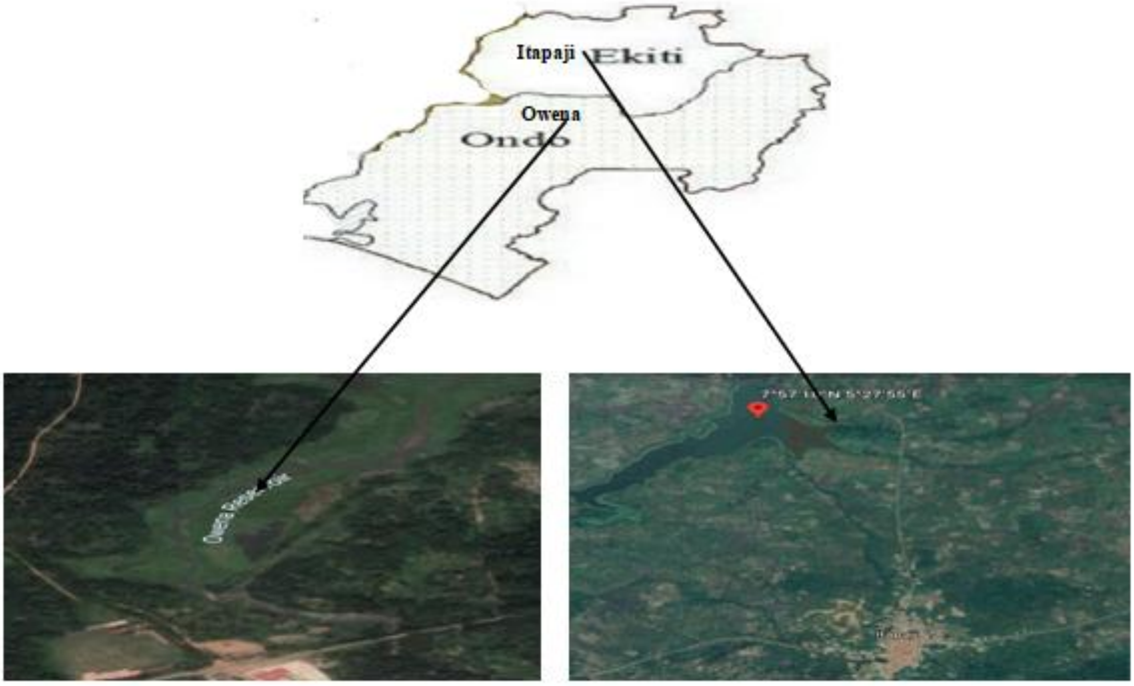

Figure 1: Map of the study areas, Itapaji and Owena towns [6, 7].

Case study area I-Itapaji-Ekiti (Ekiti State): Itapaji is located in the northern senatorial district of Ekiti state, Nigeria. It lies between latitude 7.952 ^{o} N and longitude 5.465^{o} E. It falls within the equatorial climate zone, having two major seasons: the raining season and dry season. The raining season normally occurs between April and October, why the dry season is between November and March. The community has been depending on fossil fuel and wood for lighting and energy sources. Some that can afford diesel generators depend on it for their domestic energy needs.

The village energy consumption per day is 3,943.9 kWh and the peak load is 470.4 kW. The daily load profile is shown in Figure 2. The monthly average stream flow and the solar resources data is as shown in Table no 1. The average solar radiation for the village is 4.95 kWh/m^2/ day.

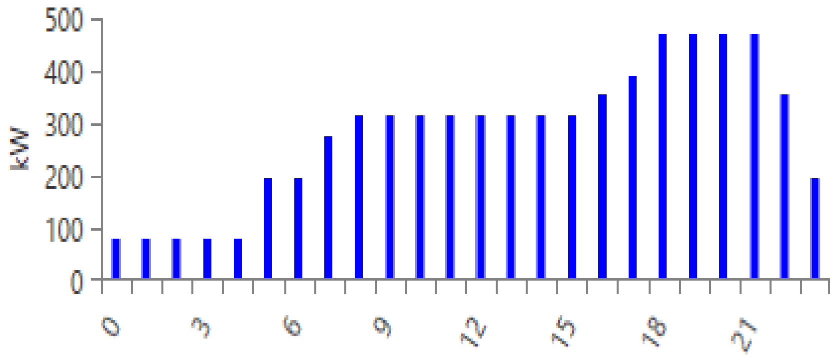

Figure 2: Itapaji Village Load Profile

Table 1: Summary of Ele river monthly average hydro and solar resources data Itapaji-Ekiti

Month	Head (m)	Discharge m^3/s	Peak sun hour (kWH/m^2)	Temp. (°c)	Clearness Index
January	0.91	4380	5.42	30.46	0.56
February	0.85	3650	5.39	31.15	0.52
March	0.82	3780	5.41	30.66	0.51
April	1.02	8220	5.35	29.82	0.52
May	1.36	17530	5.03	28.78	0.52
June	1.77	26170	4.62	27.96	0.50
July	2.11	33720	4.16	27.49	0.45
August	2.42	37300	3.77	27.34	0.40
Sept.	2.44	32220	4.37	27.64	0.42
October	2.15	23520	4.95	28.34	0.49
Nov.	1.81	16120	5.47	29.39	0.54
Dec.	1.20	7680	5.44	29.91	0.57
Annual average	**1.57**	**17861**	**4.95**	**29.08**	**0.50**

Case study area II-Owena (Ondo State): Owena is on latitude7.198o N and longitude 5.018o E and 24.4 km from Akure, the state capital. The climate here is tropical. In winter, there is much less rainfall than in summer. The average annual temperature is 25.9 °C. The rainfall here averages 1484 mm. Agriculture is the mainstay of the economy of this community and the chief products are cotton and tobacco, cacao, rubber and timber (teak and hardwoods). Two 300 kVA transformers were installed in this community. The power supply is erratic and most areas within this community have no access to electricity at all. Many have to resort to the use of diesel generators for their energy needs. The GPS aerial view of the river is as shown in Figure 1.The average energy demand for this area per day is 3,314.9 kWh and the peak load is 400.02 kW. The daily load profile of Owena is shown in Figure 3. The monthly average stream flow and the solar resources data is as shown in Table no 2. It has an annual average solar radiation of 4.95 kWh/m^2/ day.

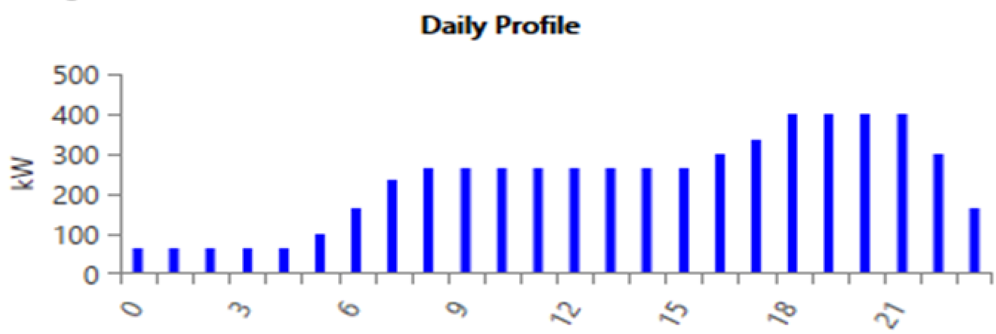

Figure 3: Owena Daily Load Profile

Table no 2: Summary Owena river monthly average hydro and solar resources data in Owena

Month	Head (m)	Discharge (l/s)	Peak sun hour (kWH/m^2)	Temp. (°c)	Clearness Index
January	0.87	4690	5.42	30.46	0.59
February	0.82	4030	5.39	31.08	0.55
March	0.82	4000	5.41	30.65	0.53
April	1.12	8220	5.35	29.96	0.51
May	1.61	17530	5.03	28.87	0.49
June	2.01	26170	4.62	28.04	0.46
July	2.40	33690	4.16	27.53	0.41
August	2.56	37300	3.77	27.29	0.37
Sept.	2.33	32220	4.37	27.63	0.42
October	2.05	23540	4.95	28.29	0.50
Nov.	1.58	16130	5.47	29.29	0.59
Dec.	1.07	7620	5.44	29.88	0.61
Annual average	**1.06**	**17928**	**4.95**	**29.09**	**0.50**

Research approach: The load demand, hydro sources and solar irradiation data of the selected study areas were used as inputs into the HOMER software. The HPS components consist of SHP, Solar PV, Diesel Generator, battery and other accessories. The mathematical models for each of them are subsequently discussed in the following sub-sections**.**

Mathematical model of small hydropower (SHP) generator: The electric power output of the SHP unit is as in (1) [19]

$$P_{SHP} = \eta_h \rho_{water} g H_{net} Q$$

(1)

Solar photovoltaic (PV) model: The maximum power output from the PV cell, P_{PV} can be calculated as in (2) [20].

$$P_{PV} = P_{r-PV}\left[\frac{G}{G_{ref}}\right]\left[1 + kT(T_C - T_{ref})\right]$$

(2)

Battery bank model: The battery capacity, $C(t)$ at a point in time t, is calculated as in (3) [21].

$$C(t) = C(t-1) - \eta_{batt}\left(\frac{P_B(t)}{V_{BUS}}\right)\Delta t$$

$P_B(t)$ is as in (4)

(3)

$$P_B(t) = E_g(t) - E_i(t)$$

(4)

This value is positive when the battery is charging.

Diesel generator (DG) model: The diesel generator is an energy conversion system from fuel to electricity with a conversion efficiency of, η_{DG} so that it can be described as in (5) [22, 23].

$$E_{DG} = \eta_{DG} E_{ff}$$

(5)

A linear model has been assumed for the fuel consumption rate (F) in litres/hour of operation by the DG [22, 23] given in (6).

$$F = (0.246 \times P_{out}) + (0.08415 \times P_{Ngen})\, litres/hour$$

(6)

The fuel cost, C_{fuel} C_{fuel} can be calculated using the formula as in (7)

$$C_{fuel} = C_{diesel} F(R_s)$$

(7)

III. Result and Discussion

Itapaji-Ekiti (Ekiti State)

Optimal configuration and the monthly average electric production: The optimal configuration for this location is the PV-BB-SHP architecture. The presence of DG only increased the cost and size of PV module, cost and quantity of batteries and capital cost of the hybrid topology compared to when it made no contribution to the electrical production. The cost of energy (COE) is 0.210 $/kWh. The RF is 100%. Thus, the setup is a good choice for implementation because the HPS is entirely renewable energy dependent. The electricity generation by individual power units of the hybrid system is as shown in Figure 4. Hydro resources accounts for 90.2 %, while PV account for 9.76 % of total electricity production of the hybrid scheme. The generation of electricity is predominantly from Hydro sources in the hybrid system because of high stream flow of Ele river

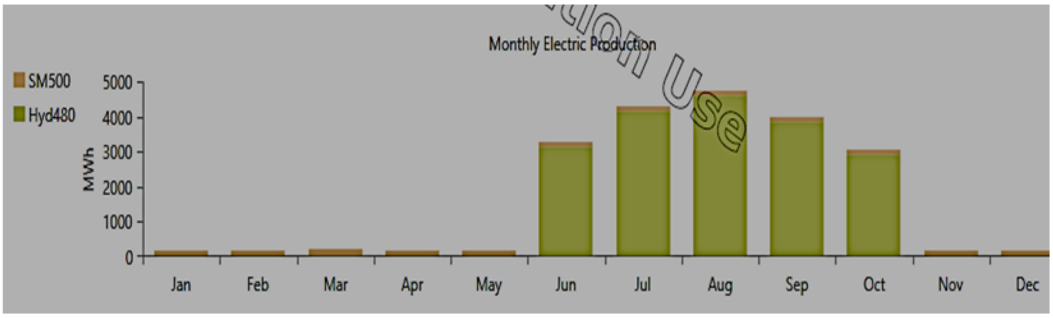

Figure 4: Monthly Average Electric Production

Emission analysis of the proposed hybrid system: The system architecture (PV-BB-SHP) by comparison with an autonomous generator resulted in saving of 594,342 litres of fuel per annum thus preventing the release of 1,570,763 kg of carbon dioxide and 1,064 kg of carbon monoxide pollution per annum. This makes the hybrid system eco-friendly.

Economic metric and simple payback period: The winning hybrid architecture is PV-BB-SHP hybrid configuration. It shows a positive Return on Investment (ROI) of 647.9 % which means the hybrid project is highly profitable for investment. The simple payback is 0.15 year. This is highly encouraging because investors do not show interest on projects that have long pay back periods. They want quick return on their investments. The present worth shows a positive value as seen in Table no 3. This means that the current system saves money over the project lifetime compared to the base case system.

Table no 3: Economic Metric and Breakeven Period of the system Architecture

Metric	**Value**
Present worth ($)	$1,395,781,00
Annual worth ($/yr)	$33,718,770
Return on Investment (%)	647.9
Internal rate of return (%)	654.1
Simple payback (yr)	0.15

Owena (Ondo State)

Optimization results and the monthly average electric production: The optimal hybrid system for the selected location is PV-BB-SHP configuration. The COE of this system is 0.255 $/kWh, and renewable resource fraction (RF) is 100%.The electricity generation by individual power units of the hybrid system is given in Figure 5. As shown in the Figure 5, PV array power production accounts for 16.7% whereas Hydro accounts for 83.3% of total electricity produced by the hybrid scheme. There is enough stream flow to run the turbine in this area

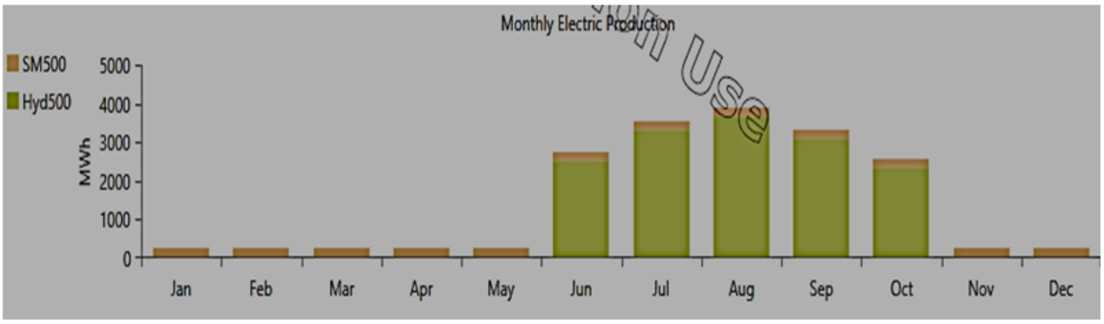

Figure 5: Annual Average Electric Production

Emission analysis of the proposed hybrid system: The 100% renewable solution as result of the selection of PV-BB-SHP Hybrid power system has the advantages of 475,666 litres of fuel consumption saving per annum, elimination of 1,256,889kg of carbon dioxide and 480kg of carbon monoxide emissions per annum from using an autonomous diesel generator as energy option.

Economic metric and simple payback period: The economic metrics in Table no 4, showed that ROI is found to be 608.3% and simple payback period is less than a year. The hybrid system is profitable. Investors are liable to recouping their investment within short time. A comparative analysis of the optimal hybrid combination for two locations was done for the two villages as in Table no 5.

Table no 4: Economic metric and breakeven period of the system architecture

Metric	Value
Present worth ($)	$1,450,466,000
Annual worth ($/yr)	$35,039,830
Return on Investment (%)	608.3
Internal rate of return (%)	613.9
Simple payback (yr)	0.16

Table no 5:Comparative analysis of the two locations-Itapaji and Owena

Location	Optimal configuration	C.O.E ($/kWh)	R.F (%)	Total litres of fuel saved /yr.	Emission reduction		Return on Investment
					CO_2	CO	
ITAPAJI	PV-BB-SHP	0.210	100	594,342	1,570.763	1,064	647.9
OWENA	PV-BB-SHP	0.255	100	475,666	1,256.889	480	608.3

IV. Conclusion

This paper evaluated the techno-economic feasibility viability of an off-grid HPS comprising of Small Hydro, Solar PV and Diesel Generator with Battery storage. The research is meant to answer the research questions bothering on whether a hybrid power system is technically viable and what topology is better for each of the two selected areas in southwest states of Nigeria. Succinctly put, a minimum of 8 feasible topologies were feasible for each state among which the optimal selection for Itapaji (Ekiti state) is PV-BB-SHP and Owena (Ondo state) PV-BB-SHP. The NPC and COE for the entire system architecture suggested for the two study areas are within acceptable standard and are almost emission free. The economic metrics also showed high investment attraction for the hybrid projects. The initial capital of a hybrid power project is usually high compared to a generator alone. Since the research has shown that HPS for each study area has high percentage return on investment and short payback period, the projects are worthwhile. Government should provide necessary financial incentives for takeoff of these projects. Government, non-governmental organizations and private sectors should join hands on implementation of research findings. Several research findings have been published but no implementation.

Considering the epileptic power supply in Nigeria and the global concern about environmental degradation, this study shows that investment in HPS is a necessity in view of its numerous energy potential and the percentage emission reduction associated with it. More so that the renewable resources abound in these southwest states and the isolated rural communities cannot easily be electrified through the national grid.

Nomenclature

Symbol	Meaning
P_{SHP}	Power output of the turbine
ρ_{water}	Density of water (1000 kg/m^3)
g	Acceleration due to gravity (9.8 m/s^2)
H_{net}	Effective head
Q	Water discharge expected to pass through the turbine (m^3/s)
P_{PV}	Output power from the PV cell
P_{r-pv}	Rated power at reference conditions
G_{ref}	Solar radiation (1000 W/m^3) at reference
G	Solar radiation in kW/m^2
T_C	Cell temperature

kT	Temperature coefficient of maximum power
$C(t-1)$	Battery capacity at previous increment
E_g	Total energy content of oil
$P_B(t)$	Batteryinput /output power
η_{DG}	DG conversion efficiency
$C_{fuelcost}$	Fuel cost
C_{diesel}	Fuel price per litre
P_{DG}	DG power

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