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Optimal Sizing and Simulation of a Sustainable Off-grid Hybrid Energy System: A Case Study of the Coastal Areas of Delta State

E. S. Kenu[1,*], R. Uhunmwangho[2], E. N. C Okafor[3]

[1, 2] Department of Electrical and Electronic Engineering, University of Port Harcourt, Choba, 5323, Port Harcourt, Rivers State, NIGERIA
[3]Department of Electrical and Electronic Engineering, Federal University of Technology, Owerri, Imo State, NIGERIA

Abstract
The off-grid coastal areas of Delta State are rich in energy resources including natural gas and solar irradiation; but do not have access to electricity. Accordingly, this paper proposes a sustainable solution for power supply in these areas using the method of simulation. Specifically, using the Hybrid Optimization Model for Multiple Energy Resources (HOMER) software, the most feasible or optimal design configuration for sustainable means of power supply for off-grid areas was presented. The result obtained was then assessed based on the various available funding options. In particular, the Public-Private-Community- Oil and Gas Partnership (PPCOP) funding model presents the most feasible solution that delivers the lowest cost of electricity (COE) to the consumer, based on the premise that some of the components of the power supply value chain are donated to the project rather than bought.

Keywords: Hybrid Energy Systems, Sustainable Systems, Off-grid, Solar, Wind, Gas Generator, Delta State

1.0 INTRODUCTION

The off-grid areas of Delta State are one of the richest parts of Nigeria in terms of natural resources, but they remain without sustainable electric power supply and the socio-economic advantages that come with it. This motivated the study into sustainable means of power supply for off-grid areas.

According to the World Bank, 85 million Nigerians do not have access to grid electricity. This represents 43% percent of the country's population, making Nigeria the country with the largest energy access deficit in the world. This lack of reliable power is a significant constraint for citizens and businesses, resulting in annual economic losses estimated at $26.2 billion (₦10.1 trillion), which is equivalent to about 2 percent of GDP [1]. The major energy sources available in Nigeria are fossil fuel (diesel, gasoline, methane gas) and hydro. Although wind and solar resources abound in Nigeria, they have not been exploited to their full potential. Several attempts have been made by various government agencies to provide electricity using diesel generators in the off-grid areas of Nigeria, including Delta State, but they have not been sustainable, because these interventions were not combined with productive use of equipment to enable the users generate more income; hence, after a while, they stopped using the facilities, as they could not afford to provide the diesel fuel and maintenance required to keep the generators operational.

It has been suggested that targeted electricity interventions that develop community skills, build access to financing, connect value chains and build market access will enable communities to use electricity more effectively and support progress to achieving Sustainable Development Goal 7 – ensuring access to affordable, reliable, sustainable, and modern energy for all [2]. The role of energy in the achievement of sustainable development goals is shown in Figure 1.

Because electricity is the major driver for the attainment of all the Sustainable Development Goals as shown in Figure 1, it is important that the electricity supply challenges of the off-grid areas be addressed, and a sustainable model developed that is applicable to all other off-grid areas in Nigeria in particular, and Africa in general. The outcome of this paper shall provide useful information for governments, intervention agencies, investors, planners and researchers who have an interest in providing sustainable electricity access to the millions who live in such areas.

In contrast to existing results, the major objective of this paper is the assessment of energy sources available in the off-grid coastal areas of Delta State to find which solution or combination of solutions would best solve the

*****Corresponding author **(Tel:** +234 (0) 8033410950**)**
Email addresses: eguonosarah@yahoo.com (E. Sarah Kenu), tripodeng@yahoo.com (R. Uhunmwangho), and encokafor2000@yahoo.com (E. N. C. Okafor)

challenge of sustainable power supply in these areas. To this end, seven years of weather data from January 2013 to December 2019 was obtained for selected locations along the coast of Delta State, and analyzed to determine the energy potential of the various sources. This study seeks to address the question of how the off-grid areas of Delta State can be provided with sustainable electricity.

Figure 1: The role of energy in the achievement of sustainable development goals.
Source: World Bank, Energy Access Report, 2017; IEA, Energy Access Outlook 2017, From Poverty to Prosperity.

2.0 MATERIALS AND METHODOLOGY

2.1 Study Area

Delta State is located in the southern part of Nigeria on latitude 5.7040° N, and longitude 5.9339° E. It was created in 1991 from the southern half of former Bendel State. It is bounded by Edo State to the north, Anambra State to the east, Rivers State to the southeast, Bayelsa State to the south, the Bight of Benin of the Atlantic Ocean to the west, and Ondo State to the northwest. On the east and south, the state is bounded by the lower course and delta of the Niger River. Asaba, on the Niger River, is the state capital. It has an area of 6,833 square miles (17,698 square km), and a population of 4,098,391 (2006 est.). Most of the state lies at an elevation below 500 feet (150 metres) in the Niger River delta. Mangrove swamps predominate in the delta and merge with freshwater swamps to the north. A maze of interconnected waterways including the Benin, Escravos and Forcados rivers which empty into the Bight of Benin, are used for transportation [3]. The major economic occupation of the people is Agriculture and Fishing. This has however suffered a major decline due to oil and gas exploration activities which has left many of the communities polluted and unfit for agricultural purposes; without any meaningful development in these areas.

The off-grid areas of Delta State have access to several energy sources which may be harnessed for sustainable production of electricity. These include access to rivers, solar radiation, winds, flared gas, and a potential for biogas (depending on the population and activities of the community).

The rivers in Delta State are mostly low-lying with a relatively slow flow. A commercially viable site for a micro hydro power project must generate at least 25kW. In order to achieve this, the average gross head must be at least 2 meters, and the average flow rate must be at least 2.07m^3/s [4]. So far, only two rivers in Delta State that meet this condition have been identified. They are the Ethiope River which has a hydroelectric power potential of 1.323MW, with an average flow rate of 31.73m^3/s and a head of 5 meters [5]; and the Iyi-Ukwu river in Oshimili Local Government area of Delta State which has a hydroelectric power potential of 1.83MW, with an average flow rate of 2.887m^3/s and a head of 76.2 meters [6].

According to Global Solar Atlas, Delta State has an average annual direct normal irradiation of 802 kWh/m^2[7]. Given that the average size of Delta State is 17,698 km^2, the average solar energy potential is about 14, 193,796 GWh per year, or 324 GW at an average solar panel efficiency of 20%. It is therefore no surprise that a total of three agreements to build solar power plants totaling about 600MW have been signed for Delta State. Two of these are between the Delta State Government and a United Kingdom (UK) Firm for 300MW, and Delta State and a Chinese Firm for 100MW [8]. The third is between a Nigerian Firm and a Singaporean firm for 200MW [9].

Using Warri to represent Delta State, the wind power potential from available records is not very encouraging. Raw wind data obtained for Warri at a hub height of 10m for the period of January 2006 to December 2010, shows a mean wind speed ranging from 3.18m/s in December to 4.54m/s in April, and a Wind Power Density of 19.68 W/m^2 in December to 64 W/m^2 in April, while the average wind power potential for an all-year-round projection is about 107.96 W [10]. Studies have shown that the average wind speeds in a particular location needs to exceed at least 6 m/s to 8 m/s for even a small wind turbine to be economically viable. Larger wind turbines typically require wind speeds of between 10 m/s to 15m/s [11]. This indicates that wind power is not an economically feasible solution for power supply in Delta State.

According to data available from the National Oil Spill Detection and Response Agency (NOSDRA) Gas Flare Tracker [12], total estimated gas flared in Delta State between March 2012 and April 2021 stands at about 653.3 million MSCF of natural gas, as shown in Figure 2. This gas, if harnessed, could have produced 65,300 GWh of electricity within the 9-year period, or about 7,256 GWh of electricity annually. This is enough to meet about 25% of the entire electricity demand of Nigeria, which stands at about 29,100 GWh as of 2018 [13]; as well as avoid the annual release of additional 3.85 million tonnes of CO_2 into the environment and save up to 255.5 Million USD per year over the period. Using this gas for electricity would also reduce other destructive side-effects of gas flaring such as environmental damage, loss of livelihood and declining health of the population living within 2 km of gas flare sites [14].

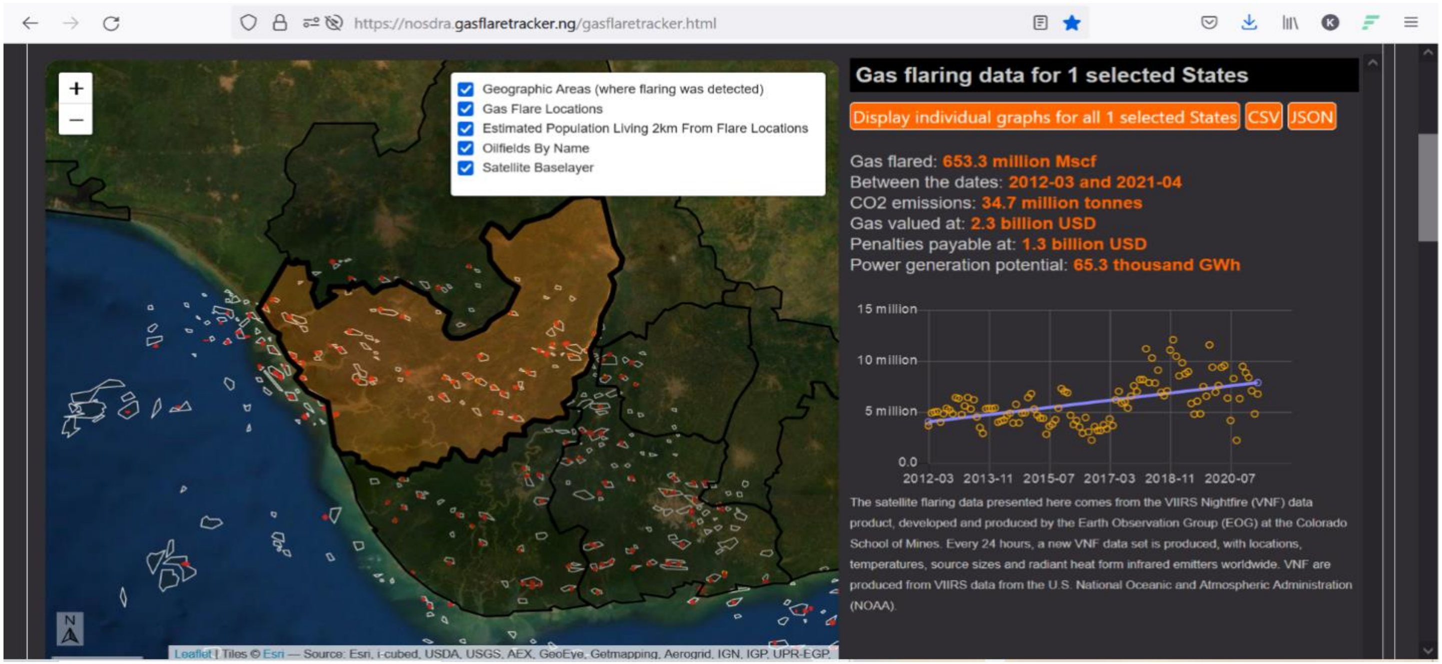

Figure 2a: Map of Delta State showing all gas flaring sites and data. Source: NOSDRA Gas Flare Tracker.

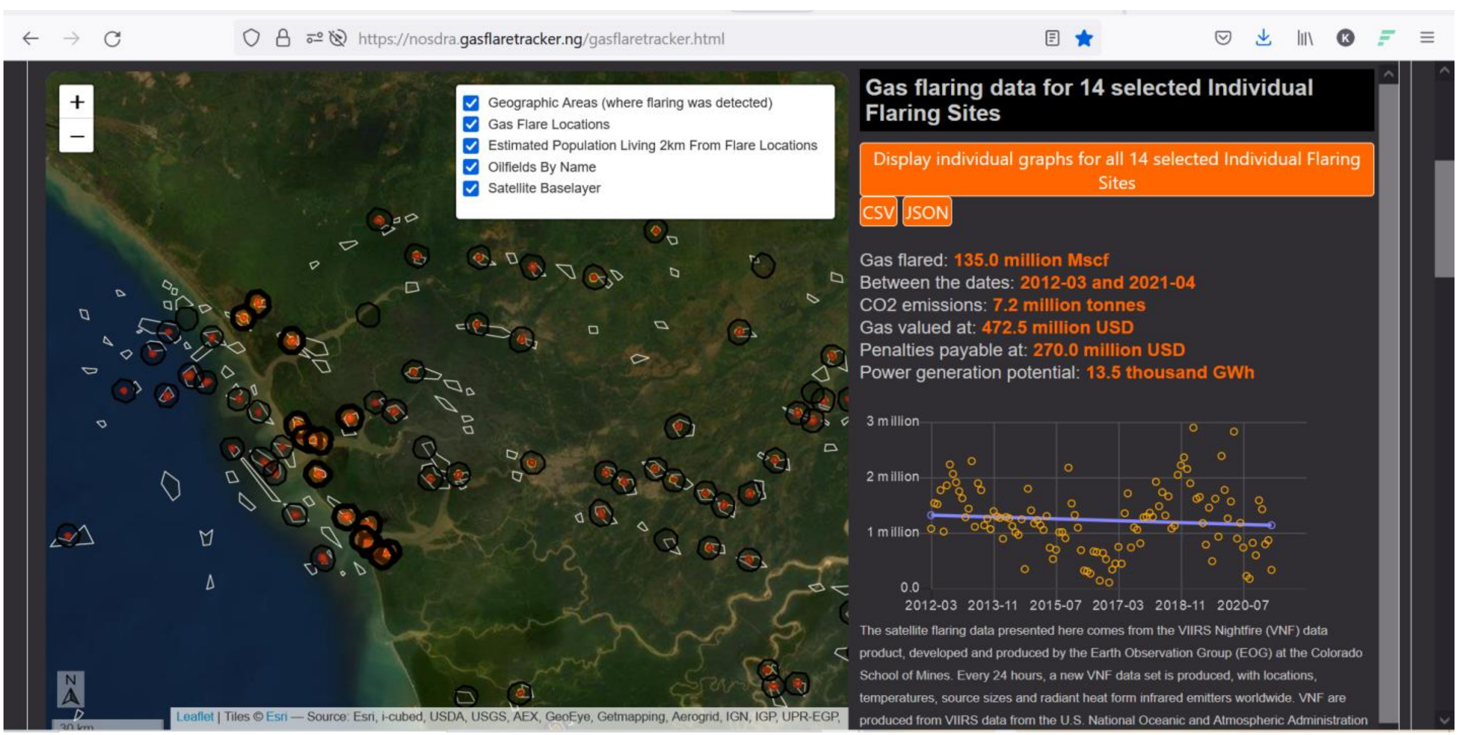

Figure 2b: Map of Delta State showing 14 gas flaring sites along the coast of Delta State Highlighted, along with their data. Source: NOSDRA Gas Flare Tracker.

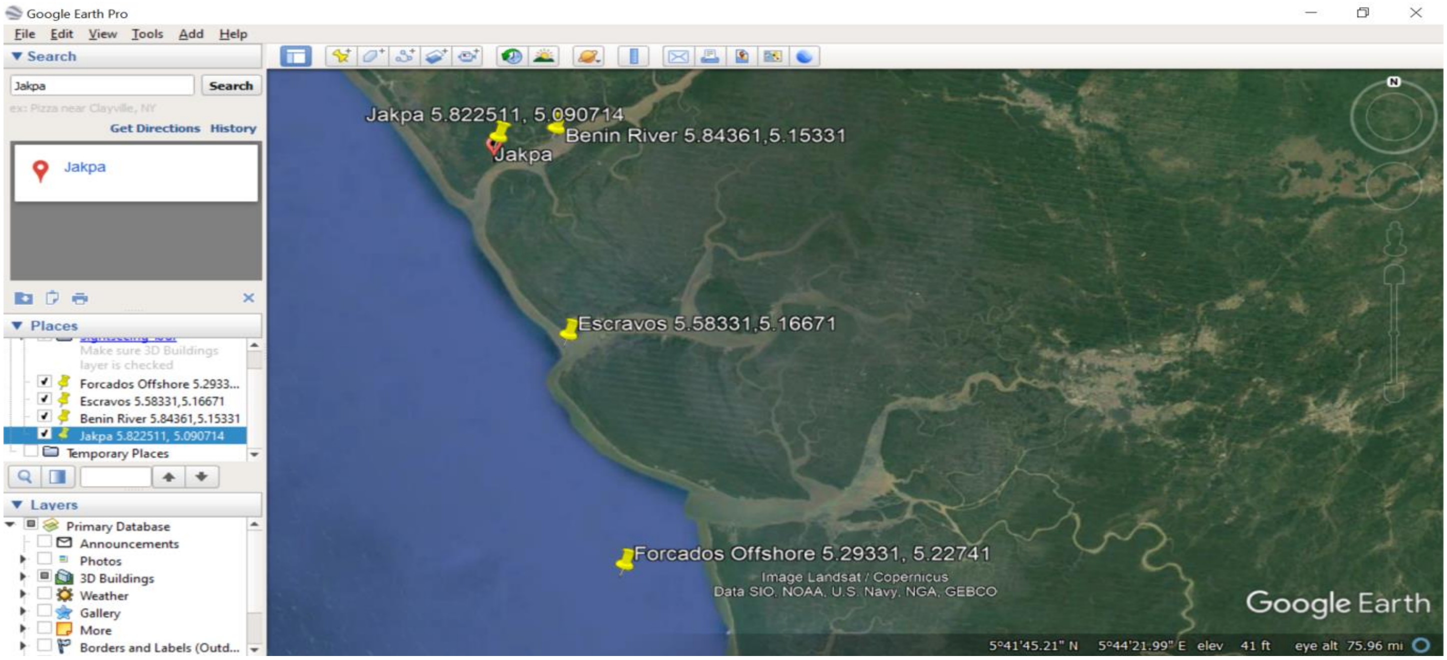

Figure 3a: Google Earth Map showing the three sample locations along the coastline of Delta State and location of Jakpa Community. Source: Google Earth

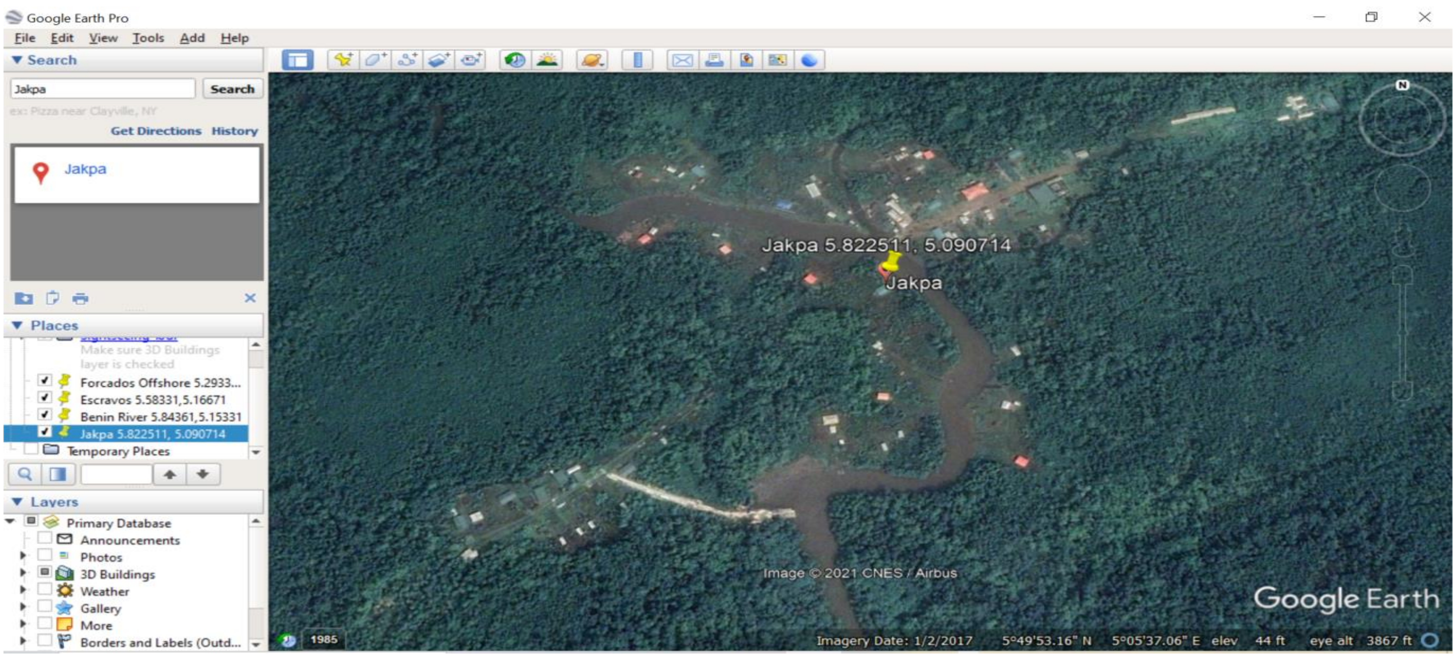

Figure 3b: Google Map of Jakpa Community in Delta State. Source: Google Earth

Jakpa Community is located at GPS coordinates N5.822511, E5.090714, and lies close to the mouth of the Benin River, as shown in Figure 3b.

Analysis of the data shown in Figure 2 reveal that 20.6% of the gas being flared is located in the coastal areas of Delta State, and if harnessed could have yielded 13,500 GWh of electricity over the last 9 years.

It is therefore important that power supply solutions involving the use of natural gas be prioritized in Delta state as a means of both ending the harmful and wasteful gas flaring, as well as boosting the socio-economic development of these rural areas.

A review of existing literature available online revealed that a hybrid system consisting of Solar PV, Natural Gas Generator and Battery Storage System could be considered a sustainable solution for the electric power supply challenges in Delta State; although no case study was found for Delta State in particular.

For the purpose of this study, Jakpa community was selected to represent a typical off-grid community located close to the mouth of the Benin River. Weather data collected for the Escravos and Benin river area as shown in Figure 3a, yielded the same values; indicating that the weather characteristics remained fairly constant along the entire coast of Delta State.

Jakpa has a tropical climate with two distinctive seasons - the dry season which spans November to April, and the wet season which spans May to October, with a brief dry spell in August. From December to February, the dry harmattan wind blows over the area. Jakpa has an estimated population of 2,250, based on the 1990 survey of 850 persons [15].

Using Nigeria's per-capita electricity consumption of 144.5 kWh per person as estimated by the World Bank in 2014 yields an estimated annual electricity demand of 325,992 kWh per year, or an average load demand of about 37kW. The major electricity need of this community is for refrigeration or drying of fish, as fishing is their predominant economic activity. The estimated load profile of Jakpa Community is shown in Figure 4.

0:00 - 1:00	35.00
1:00 - 2:00	35.00
2:00 - 3:00	35.00
3:00 - 4:00	35.00
4:00 - 5:00	35.00
5:00 - 6:00	38.00
6:00 - 7:00	40.00
7:00 - 8:00	35.00
8:00 - 9:00	38.00
9:00 - 10:00	39.00
10:00 -11:00	39.00
11:00 - 12:00	39.00
12:00 - 13:00	35.00
13:00 - 14:00	38.00
14:00 - 15:00	39.00
15:00 - 16:00	39.00
16:00 - 17:00	39.00
17:00 - 18:00	39.00
18:00 - 19:00	35.00
19:00 - 20:00	40.00
20:00 - 21:00	38.00
21:00 - 22:00	38.00
22:00 - 23:00	35.00
23:00 - 24:00	35.00

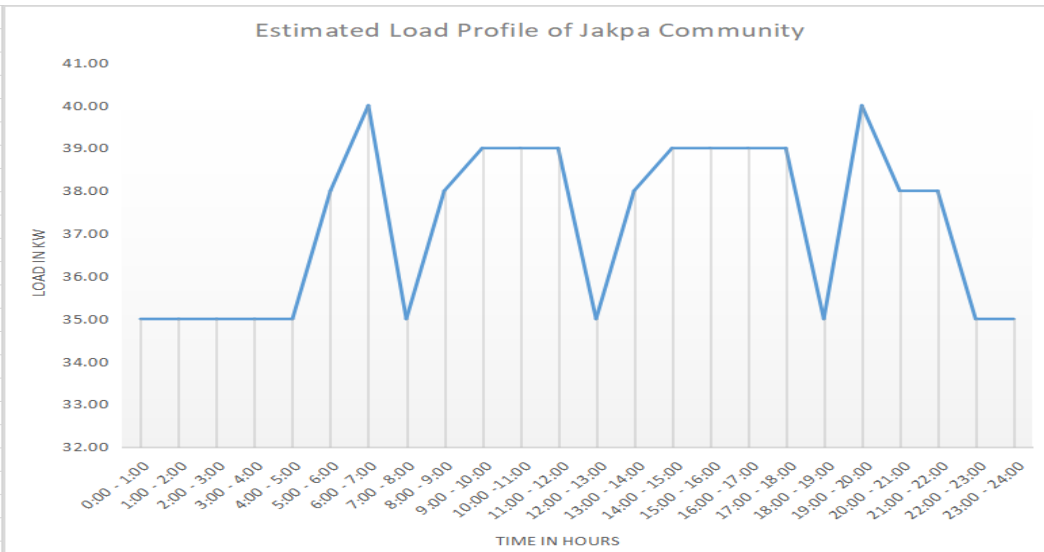

Figure 4: Estimated load Profile for Jakpa Community off the Coast of Delta State

2.2 *Weather Data Collection for the Coastal Areas of Delta State*

The daily weather data for the coast of Delta State spanning a period of seven years (January 2013 to December 2019) was obtained from a NASA satellite-based weather station. Table 1 shows the weather data collected from the mouth of the Benin River along the coast of Delta State over a seven-year period of 2013 to 2019, condensed into monthly averages for use in the HOMER software.

Table 1: Summary of Seven-Year Monthly Average Weather Data Obtained for the mouth of the Benin River, along the Coast of Delta State, used for simulation in HOMER

MONTH	LATITUDE (Degrees)	LONGITUDE (Degrees)	Temperature (Degrees Celcius)	Wind Speed @50m Height	Global Horizontal Irradiation in kWh/m^2/day
JAN.	5.84361	5.15331	26.09	4.91	5.04
FEB.	5.84361	5.15331	27.12	4.59	4.91
MAR.	5.84361	5.15331	27.41	3.95	4.46
APR.	5.84361	5.15331	27.38	3.82	4.86
MAY.	5.84361	5.15331	26.88	3.81	4.38
JUN.	5.84361	5.15331	25.99	3.64	3.59
JUL.	5.84361	5.15331	25.28	3.68	3.26
AUG.	5.84361	5.15331	24.97	3.72	3.50
SEP.	5.84361	5.15331	25.31	3.66	3.43
OCT.	5.84361	5.15331	25.97	3.83	4.21

MONTH	LATITUDE (Degrees)	LONGITUDE (Degrees)	Temperature (Degrees Celcius)	Wind Speed @50m Height	Global Horizontal Irradiation in kWh/m^2/day
NOV.	5.84361	5.15331	26.76	4.42	4.79
DEC.	5.84361	5.15331	22.71	4.40	4.43

2.3 Simulation of Optimal Solution Using HOMER

Hybrid Optimization Model for Multiple Energy Resources (HOMER) is a software application used to design, simulate, and optimize various configurations of hybrid energy systems; in order to evaluate technically and financially, the most viable options for off-grid and on-grid power systems for remote, stand-alone, inter-connected and even utility power generation applications.

In general, the Homer software is a trusted optimization tool used by several system designers, project developers and government agencies globally [16-20]. Here in Nigeria, it is one of the software being used by the Renewable Energy Division of the Rural Electrification Agency (REA) to plan solar minigrids and microgrids. Specifically, Homer software provides the most robust, accurate, technically optimal and maximally cost-effective solutions to hybrid power systems design. In the context of the design and development of energy distribution networks, whether hybrid microgrids or distributed generation systems, the Homer software solution is capable of optimizing project economics, allowing the user to efficiently determine least cost options; simulate real world performance to ensure that plans resemble actuals in terms of changing load growth, changing weather patterns, and battery lifetime performance. The software requires certain design inputs to be entered into the system in order to generate the desired output options.

For the hybrid energy system considered in this work, the following data inputs are required:

1. Geographical Co-ordinates of the Site.
2. The load profile data as shown in Figure 4.
3. The type of Solar PV Module to be used for the simulation. It can be selected from the drop-down menu in the HOMER software. If it is not available, the technical specifications can be inputted into the library and then selected for use.
4. Type of Generator to be used. This is also selected from the drop-down menu. A generic gas generator that meets the required specifications can be selected.
5. A wind turbine is also selected from the HOMER library or inputted into the software, in order to allow the system to consider the possibility of using wind power in the simulation options.
6. Type and size of individual battery units to be used is selected from the drop-down menu. For an environmentally friendly and easily maintained option, a generic lithium battery of 1kWh is selected.
7. Type and price of fuel per litre is also selected from the available options in the model.
8. Average Solar Irradiation in kWh/m^2/day is also entered into the HOMER Model from the data provided in Table 1.
9. Average wind speed in m/s and height of anemometer at which the speed is recorded is also entered from the data provided in Table 1.

Once these values were entered into the HOMER Software, thousands of simulated options were generated, all the while trying to achieve a system with an optimal life-cycle cost. The feasible solutions were presented, while the ones that were not feasible were discarded. HOMER performed the simulation, optimization and sensitivity analysis of different system configurations simultaneously. From the array of results, the hybrid renewable energy system that presents the lowest cost of electricity (COE) and net present cost (NPC) was selected, which satisfied the demands of the load profile. This is a very important feature as it helps decision makers and project developers determine whether the project is a good investment of scarce resources or not.

3.0 RESULTS AND DISCUSSION

3.1 Selection of Power Supply Solution based on HOMER

From the load profile values in Figure 4, HOMER calculated the Average Load in kWh/day to be 893kWh, Average Load in kW to be 37.21 kW, and Peak Load in kW to be 46.32 kW as shown in Figure 6.
Setting the day-to-day random variability of the load to a minimal factor of 5%, and time-step variation to 0%, yielded a load factor of 0.8 or 80%, which is good for a power generating system to be considered feasible.

The Sensitivity cases display the various solution options based on the different values of solar irradiation within the range of 1.57 kWh/m^2/day and 2.74 kWh/m^2/day. The results showed that the changes in solar irradiation within this range did not change the solar electricity production figures.

The optimization results were presented in categorized and overall options. The categorized table of options showed the list of best solution options available in the simulation, from the most feasible option to the least feasible option, based on their net present cost, in combination with other factors such as renewable fraction, low-capacity shortage, excess electricity generation, fuel consumption and so on. Figure 7 shows the results dashboard for the sensitivity analysis and optimization for the HOMER simulation process.

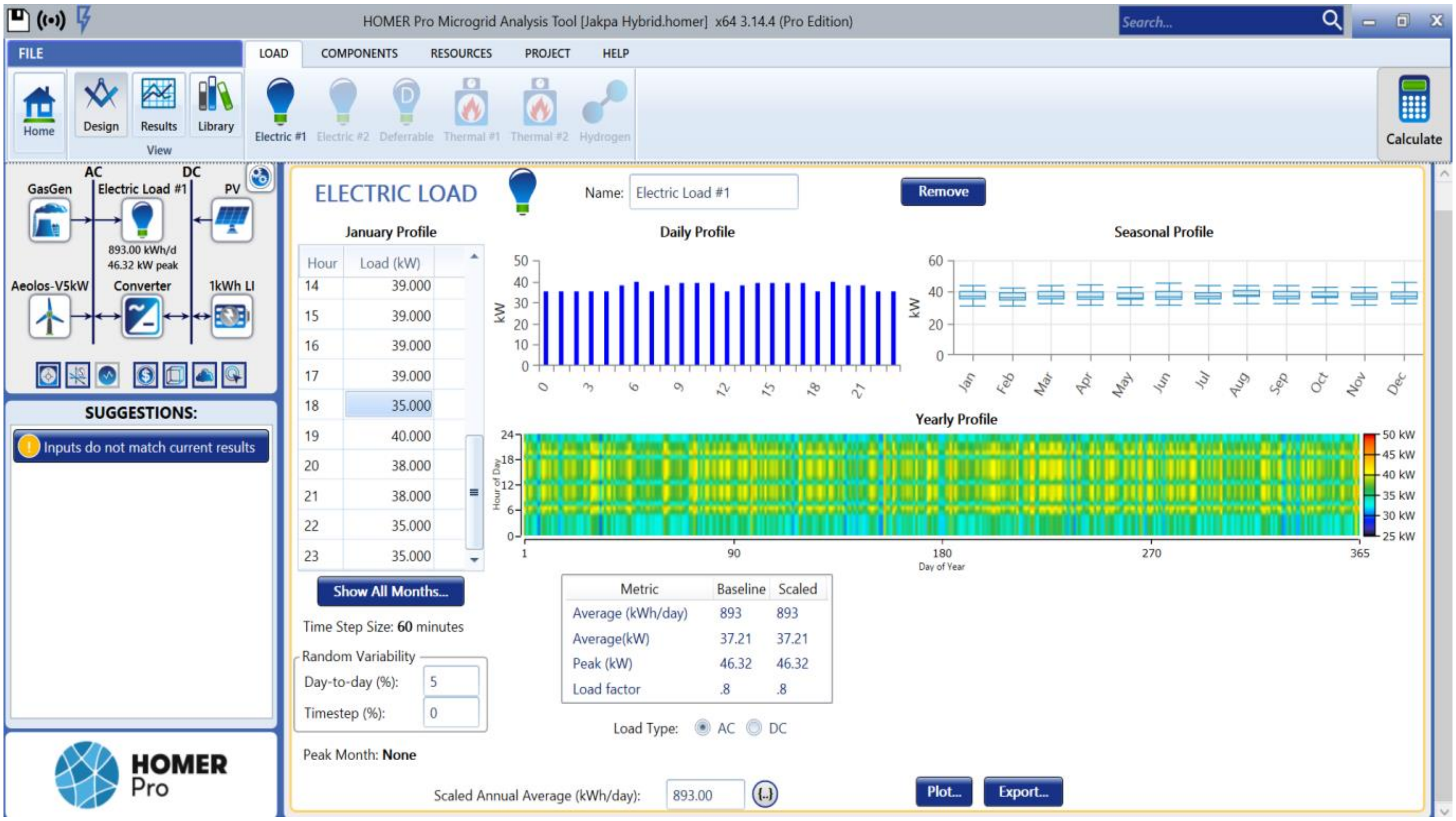

Figure 6: Annual Load Profile of the Proposed System

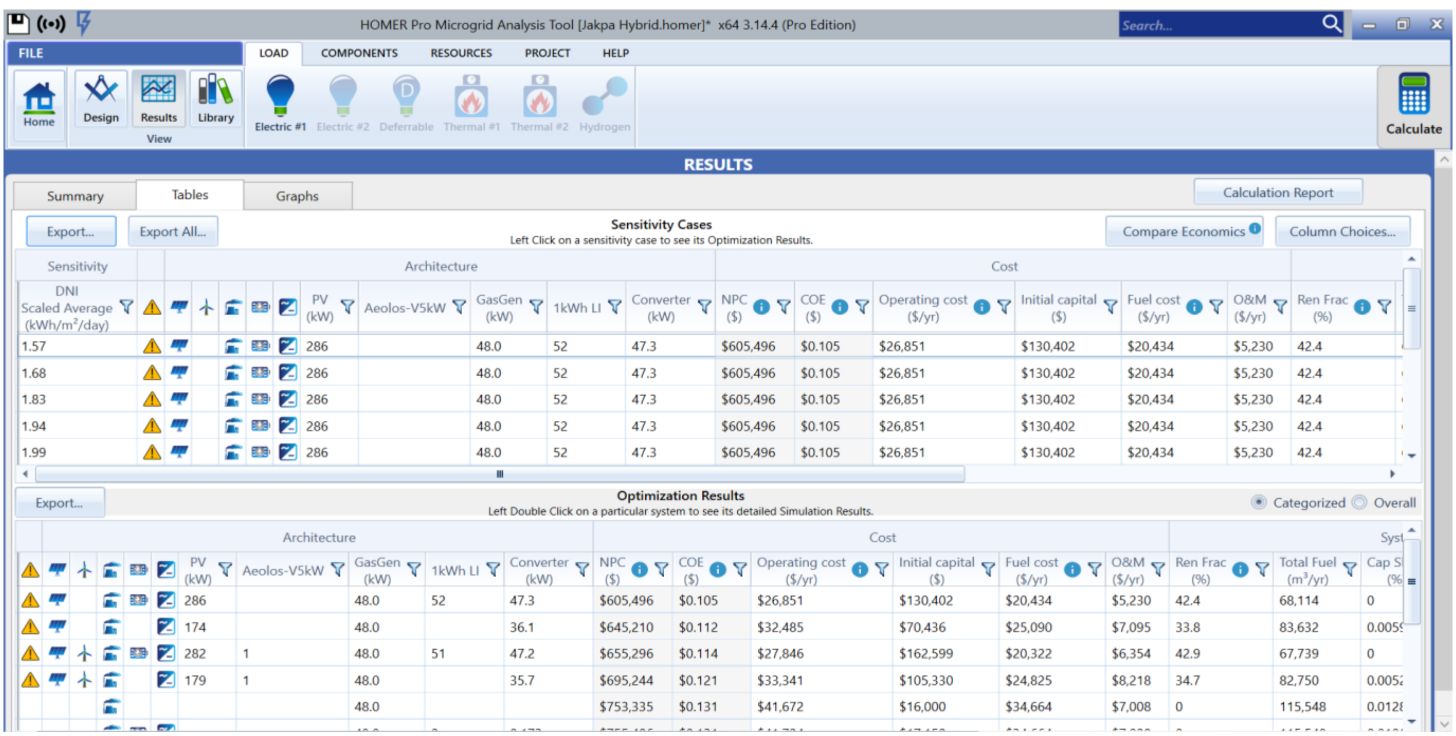

Figure 7: Results Presentation Dashboard

Although 32,252 possible configurations of the proposed hybrid energy system were simulated, only 24,585 were found to be feasible. Of this feasible number, only the 6 most optimal configurations were considered for analysis in this study. The most feasible or optimal design configuration presented in the results dashboard is the one with the lowest NPC, lowest LCOE, relatively high renewable fraction, lowest capacity shortage, and relatively lower fuel consumption system.

Table 2 shows the best six configurations of optimized results from the lowest LCOE being the best configuration, to the highest LCOE, being the least desired configuration. In simulating these system configurations, cost of gas fuel at \$0.3/m^3, annual inflation rate of 5%, discount rate of 8%, annual capacity shortage of 0%, project lifetime of 25 years, and scaled load demand at 100% of baseline load, were inputted into the HOMER software for simulation calculations.

Table 2: Details of Six Samples of Possible Hybrid Energy System Configuration for Jakpa Community. Adapted from HOMER Pro Micriogrid Analysis Tool

Configuration Type	Architecture/ PV (kW)	Architecture/ Aeolos-V 5kW	Architecture/GasGen (kW)	Architecture/ 1kWh LI	Architecture/ Converter (kW)	Cost/ NPC (\$)	Cost/ COE (\$)	Cost/ Fuel cost (\$/yr)	System/ Ren Frac (%)	System/ Excess Elec (%)	System/ Unmet load (%)	System/ Elec Prod (kWh/yr)
Type 1	286.41		48.00	52.00	47.33	605,496.30	0.105	20,434.21	42.44	40.84	0.000	563,556.70
Type 2	174.48		48.00		36.06	645,209.60	0.112	25,089.69	33.76	25.44	- 0.000	444,902.40
Type 3	281.65	1.00	48.00	51.00	47.19	655,295.80	0.114	20,321.57	42.88	40.46	0.000	559,772.10
Type 4	178.55	1.00	48.00		35.71	695,243.80	0.121	24,825.13	34.70	26.47	0.000	451,118.10
Type 5			48.00			753,335.20	0.131	34,664.41	-	-	- .0	325,945.00
Type 6			48.00	2.00	0.17	755,405.90	0.131	34,664.41	-	-	- .0	325,945.00

The configuration types are described as follows:

Type 1: 286.41 kW Solar PV + 48 kW Natural Gas Generator + 52 kWh Lithium-ion Battery Bank + 47.33 kW Converter

Type 2: 174.48 kW Solar PV + 48 kW Natural Gas Generator + 36.06 kW Converter

Type 3: 281.65 kW Solar PV + 1.0 kW Wind Turbine + 48 kW Natural Gas Generator + 51 kWh Lithium-ion Battery Bank + 47.19 kW Converter

***Type 4*:** 178.55 kW Solar PV + 1.0 kW Wind Turbine + 48 kW Natural Gas Generator + 35.71 kW Converter.

***Type 5*:** 48 kW Natural Gas Generator only.

***Type 6*:** 48 kW Natural Gas Generator + 2 kWh Lithium-ion Battery Bank + 0.17 kW Converter

The diagram shown in Figure 8 is the configuration of the type 1 hybrid system.

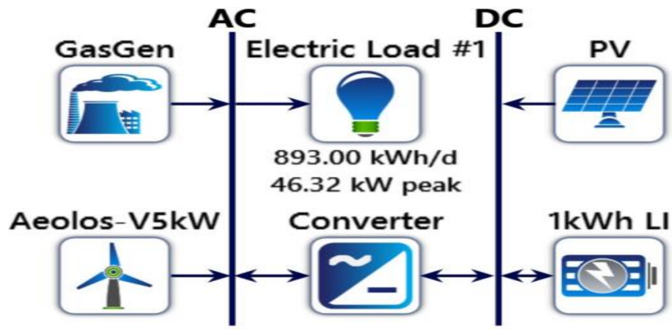

Figure 8: Configuration of Proposed Parallel Hybrid Energy System Designed using HOMER.

Table 3: Overview of the selected system configuration type (Type 1). Adapted from the HOMER Pro System Simulation Report

System Components	**Name**	**Size**	**Unit**
Gas Generator (Gasgen)	Kohler 48RCLC	48.0	kW
PV	Generic flat plate PV	286	kW
Storage	Generic 1kWh Li-Ion	52	strings
System converter	System Converter	47.3	kW
Dispatch strategy	HOMER Load Following		
Net Present Cost		605,496	US $
Capital Expenses (CAPEX)		130,402	US $
Operating Expenses (OPEX)		26,851	US $
LCOE		0.105	US $/kWh
CO_2 Emitted		131,506	kg/year
Fuel Consumption		68,114	m^3/year
Simple Payback		7.15	years
Discounted Payback		8.11	years
Internal Rate of Return (IRR)		12.5	%

Table 4: Electrical Summary of the selected system configuration type (Type 1). Adapted from the HOMER Pro System Simulation Report

A	**Excess and Unmet Load**		
	Description	***Value***	***Units***
	Excess Electricity	230,138	kWh/yr
	Unmet Electric Load	0	kWh/yr
	Capacity Shortage	0	kWh/yr
B	**Energy Production Summary**		
	Component	***Production (kWh/yr)***	***Percent***
	Generic flat plate PV	375,928	66.7
	Kohler 48RCLC	187,629	33.3
	Total	***563,557***	***100***
C	**Energy Consumption Summary**		
	Component	***Consumption (kWh/yr)***	***Percent***
	AC Primary Load	325,945	100
	DC Primary Load	0	0
	Deferrable Load	0	0
	Total	***325,945***	***100***

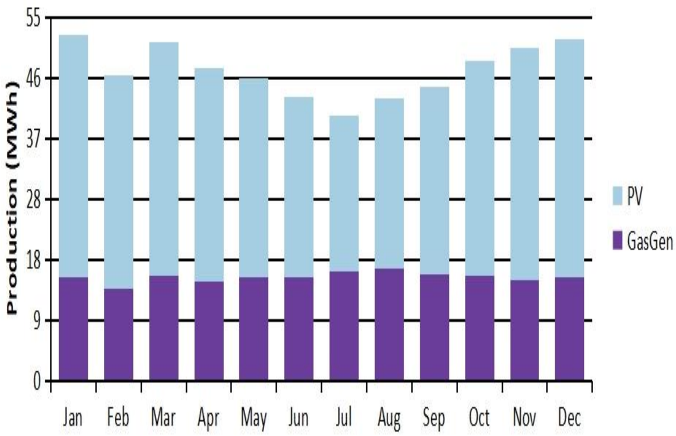

Figure 9: Energy Production Profile of the selected system type. Adapted from HOMER Pro System Simulation Report

3.2 Selection of Power Supply Solution Based on Funding Model

Although the cost is the major deciding factor for the selection of a particular hybrid energy system configuration using the HOMER software, source and type of funding as well as the availability of resources could present alternative solutions for the selection of the most feasible solutions for sustainable power supply in the coastal areas of Delta state. For example, in the 14 communities that have gas flaring sites shown in Figure 2b, the type 5 system configuration made up of the gas generator alone, could become the most feasible solution; if the gas generator and a daughter station for the cleaning and compressing of the gas were provided at the flare site by the operating company, as part of the conditions precedent to allowing their operations to continue in such community. In this case, the cost of the generator as well as cost of gas would be set to zero in the funding model, and only the operations and maintenance costs of the system would remain, thus, drastically reducing the NPC as well as LCOE. Equipment that encourages productive uses of electricity can be either bought by donor agencies, by private investors or by the community itself, thus stimulating economic growth and ability to pay for the sustainability of the electricity for as long as the gas remains available. Such collaboration for the delivery of sustainable development through the provision of electricity has been described by Matthew Edevbie of Income Electrix Limited as the Public-Private-Community- Oil and Gas – Partnership (PPCOP) model. This is a model which, if embraced in Delta and similar oil producing states, could turn the rural off-grid areas into thriving economic destinations, and create an ecosystem where oil and gas exploration can co-exist with sustainable development in the host communities.

4.0 CONCLUSION

The choice of power supply solution for the coastal area of Delta state depends not only on the cost of the system or renewable fraction of the system, but also depends on the funding model to be applied to the realization of the project. If some components of the power supply value chain can be obtained for free or at a lower concessionary rate, the system configuration with the lowest cost of electricity to the consumer should be adopted. In addition to this, a productive use system must be put in place to ensure that the consumers use at least 40% - 65% of the electricity for income generating activities, in order to guarantee a sustained ability to pay for and maintain the facilities.

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