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Harnessing Solar and Wind Power for Hybrid Stand-alone Energy System: The Case of Coastline Communities in Delta State of Southern Nigeria

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Abstract- Most of the communities and towns in the riverine and coastline areas of Delta state of southern Nigeria have renewable energy potentials that have not been tapped. Though, these communities are rich in oil and gas deposits, however, as the world is gradually moving away from fossil fuel consumption, it is imperative to harness alternative sources of energy in this region. Therefore, emphasizes should be made in providing sustainable power supply for these off-grid communities, for economic growth and sustinable development. This study was undertaken to find a sustainable solution of the off-grid riverine and coastline areas of Delta State, Nigeria; by obtaining the weather characteristics of areas along the coastline and designing a solution that can be applied to the communities in this region. The areas considered in this study are the Escravos River, Forcados River and Benin River, comprising twenty six communities. A hybrid renewable energy system was developed considering the various communities in the region as a case study. The hybrid optimization of multiple energy resources software was employed in the study for evaluation of the prototye model. The results obtained from the study reflect that the electricity needs of the communities along the coastline areas of Delta State can be met with the design, simulation and construction of an autonomous hybrid microgrid either as a central arrangement for a cluster of communities, or as an individual arrangement for each community.

Keywords: Renewable Energy; Fossil fuels; PV cells; Wind energy; Grid, Coastline communities.

1. Introduction

The generation of electricity from renewable energy resources is fast becoming a key objective of many countries. The driving force behind this is the discovery of the link between non-renewable fossil fuels and environmental degradation. Climate change has become a major concern, leading to prediction of a global temperature rise of 3-5 °C, within 50 years and an increase in climatic variability [1]. With the predicted decline in the amounts of non-renewable resources over the next few decades [2], it became clear that alternatives to fossil fuels are needed. In order to fight climate change issues, many countries are harnessing potential renewable energy sources within their reach. The harnessing of hydropower [3, 4], solar and wind energy is on the rise daily. Countries with coastlines have particularly valuable renewable energy resources, in the form of tidal currents, waves, onshore and offshore wind. Coastal waters are extensive and the associated renewable energy resources are plentiful and predictable [5, 6]. However, due to the instability of some of these renewable sources, due to poor or bad weather, a hybrid combination of any two or more sources has been widely implemented. The Hybrid Energy System (HES) is the engineering design of hybridizing power supply components or pairing them to produce a common electricity output for powering loads. For example, arranging diverse energy resources such as solar, wind and battery energy storage to work concurrently [7]. Based on the literature, it has been highlighted that although the initial capital investment cost for deployment of a Hybrid Renewable Energy Sources (HRES) is high, there are numerous benefits of deploying such systems into an existing grid power system or as a standalone power system [8]. Some advantages obtained include greenhouse gas emissions reduction in operations and reduced or eliminated fuel cost due to free energy sources like sunlight, water and wind. In the literature, new or existing algorithms to provide better analysis and integration of HRES, were analyzed. It was concluded that HRES have more potential in achieving power stability than single energy sourced renewable energy systems. However, in relation to achieving sustainable power supply in off-grid areas, little or no attention has been given to coastal areas in Nigeria and the unique energy potentials of such areas.

Most of the communities located in the riverine and coastline areas of Delta state, in southern Nigeria, have remained without sustainable electricity, in spite of the immense oil wealth that has been extracted from these areas over the last fifty years. The prevailing reason has been that these coastline communities are often located too far away from the electricity grid to have access, as the cost of extending the grid to such places is often prohibitive [9]. This has caused such communities to remain in poverty, as the availability of sustainable electricity is the single most important driver of socio-economic growth and development in any society [10]. For example, in Burutu coastal town, which is one of the regions of this study, located in Burutu local government area, in Delta state, about eighty (80%) percent of the households are currently connected to two existing diesel generators of 575 kVA and 175 kVA, owned by the Nigeria Port Authority and Local Government Council, respectively. This form of power supply is not reliable due to the high cost of diesel fuel. It is also not adequate, thus causing most people to resort to power self-generation. The remaining 20% are not connected to the power supply, and rely on the use of unclean forms of energy such as kerosene lanterns, dry cell batteries, candles, and so on, which are not only more expensive than electricity in the long run, but also pose the risk of explosion and fire outbreak [11]. This deplorable situation has led to persistent poverty in the region, as well as a deep sense of injustice and deprivation, which has, in turn, fueled high youth illiteracy, restiveness, pipeline vandalism, kidnapping, and other criminal activities in the region [12, 13].

In order to breach the research gap, this study goes into detail about the environmental conditions of the coastal area of Delta State, in Nigeria, highlighting the power generating potential of both the available renewable energy resources as well as the non-renewable energy resources; and using this in information for the design of a practical, sustainable power supply for these areas. A further research gap gleaned from the available literature was in the area of analysis of wind power generation.

In order to breach the research gap, this study goes into detail about the environmental conditions of the coastal area of Delta State, in Nigeria, highlighting the power generating potential of both the available renewable energy resources as well as the non-renewable energy resources; and using this information for the design of a practical, sustainable power supply for these areas. A further research gap gleaned from the available literature was in the area of analysis of wind power generation. The available studies seemed to assume that once a wind speed achieved the cut-in range, it was sufficient to generate useful electricity. However, the examination of wind power curves of any given turbine shows that the cut-in wind speed only produces a maximum of twenty percent (20%) of the rated power of the turbine. Hence, for a cost-effective wind power installation, the available wind speed at the hub height must be equal to or greater than the rated wind speed.

This paper presents a design and simulation of a replicable autonomous hybrid energy system to power coastline communities in Delta state, southern Nigeria. The data of the available solar and wind potential of the coastline communities along the Benin River, Escravos River and Forcados River, were obtained in this study, in order to determine the maximum amount of solar and wind energy that can be sustainably generated in this region using the applicable mathematical models. The evaluation of the solar and wind power that can be generated at the site, using the acquired weather data by applying it to a suitable mathematical model for wind power generation, was also investigated. More so, the generation of input data for the simulation of an optimal hybrid energy system for the coastal communities in Delta state, Nigeria based on the location of the study was presented. Furthermore, the study was evaluated using the Hybrid Optimization of Multiple Energy Resources (HOMER) software, and the optimal system configuration of the hybrid energy system used for power supply in off-grid coastal community, were presented in terms of feasibility and sustainability.

2. Significance of the Study

The coastline towns of Delta state, in southern Nigeria have rich agricultural and energy resources and can be developed into thriving economic hubs supporting large populations, if the enabling environment to attract investments to this area is created in a timely manner. This is the motivation behind this study, based on sustainable electric power supply solutions that can be applied to these and other similar communities.

The theoretical significance of this study is that it provides a foundation and relevant data for other researchers engaged in similar work in the global academic community at large, to develop improved solutions. The technical significance of this study is to provide sound technical information that can be used by practicing Engineers, project developers and equipment manufacturers to design sustainable solutions for coastline communities like those in Delta state, Nigeria. The policy significance of this study is that the outcome will help corporate and government policy makers to draft relevant policy statements towards the implementation of solar and wind hybrid systems in coastline regions. Nigerian Institutions like the Nigerian Electricity Regulatory Commission (NERC) will thus be better able to set up comprehensive guidelines for hybrid systems in off-grid locations, with due consideration for environmental and technical sustainability.

3. Description of the Case Study Locations

The study area for this research is the entire coastline of Delta state, Nigeria. Weather information was obtained from the Nigerian Meteorological Agency (NMA) for the following reference points: 5.293310 N, 5.227410 E off the coast of

Forcados (about 14.6km out from Ogulagha terminal); 5.583310 N, 5.166710 E at the mouth of the Escravos river, where it meets the Atlantic Ocean (about 4.3km out from Ogidigben); and 5.843610 N, 5.015331 E near the mouth of the Benin River, where it empties into the Atlantic Ocean. The closest community to this reference point is Jakpa community, as shown in Figures 1-3. Analysis of the weather information in the study location showed that the weather conditions along the entire coastline of Delta state remained fairly uniform within a radius of 65km. Since Jakpa community in Warri North local government area of Delta state is the closest community to the Benin River reference point, it was randomly selected as a case study to represent all the communities that lie along the coast of Delta state, in harnessing the renewable energy potentials in this region.

Jakpa community is situated on the GPS coordinates N5.822511, E5.090714, and lies close to the mouth of the Benin River, as shown in Figure 2. It consists of two sections, namely Jakpa and Jakpa-Tie. Reference [14] did a survey of Jakpa community and reported that, as at 1990, the community has a primary school, dispensary, church and shops. It also has a bore-hole for provision of potable water, and a community - operated diesel generator. 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 occurring anytime within the Figure 2: Delta State Coastline Region [16].period of July to August. From December to February, the dry harmattan wind blows over the area. The average annual rainfall is 266.7 centimeters, with an average temperature of 30oC (80oF). Due to the closeness of Jakpa community to the Atlantic Ocean, the community is susceptible to flooding and overflowing of river banks during high tide, which happens more frequently in the wet seasons because of heavy rainfall. It is interesting to note that the study area also falls within the gas flaring zone of Delta State, Nigeria.

Polycrystalline solar panels, on the other hand, are rectangular with no rounded edges and have a grainy, blue-coated appearance due to the imperfect crystal structure of their cells. As the name implies, they are made by melting many lower purity silicon crystals together, making them less efficient than monocrystalline cells with an efficiency rate of 13% to 17%, and they also take up more space to generate the same amount of power as monocrystalline cells. They are less expensive than monocrystalline panels, however, because the manufacturing process is simpler and produces less waste after the melting process, making them more environmentally friendly. Polycrystalline solar panels, like monocrystalline panels, are long-lasting and durable, making them an excellent choice for frugal homeowners. [6].

4. Estimated Load Profiles of the Coastal Communities around the Forcados River

This study considers seven out of the many Coastline Communities around the Forcados River area of Delta State in southern Nigeria. Again, their power supply could be provided

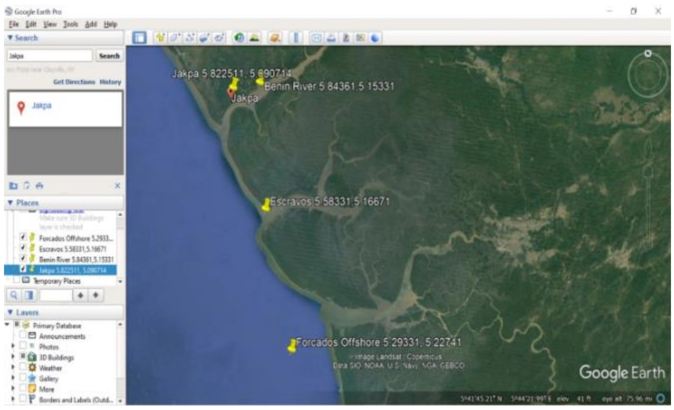

Figure 1: Niger Delta Coastline Regions [15].

Figure 2: Delta State Coastline Region [16].

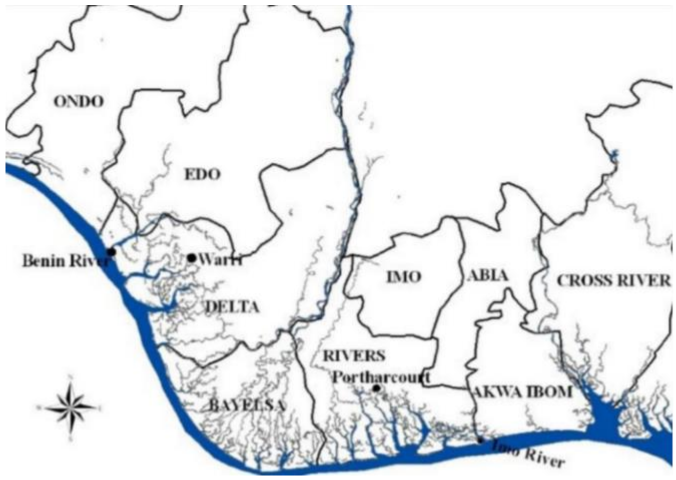

Figure 3: The three sample locations of the case study.

for in two ways- the construction of a central autonomous hybrid microgrid which consists of a central power plant generating electricity at 11kV, stepping it up to 33kV, and then radiating 33kV transmission lines and underground (submarine) cables from the central power plant to each of the seven communities, or installing individual microgrids in each of the seven communities. Since the load consumption patterns are similar throughout the communities in this area, the load profile curves for each of the seven communities will be similar, only the magnitude of power consumed per time would change. The load profile for the central power plant (CPP) follows that of the individual communities, as the only load on the CPP is the ones coming from the communities. From Table 1, the central power plant is estimated to have a peak load of about 2MW. Applying a load demand factor of 0.7 for the 5th year, which was scaled up from 0.5 in the 1st year to allow for demand growth, yields an average load demand at the busbar of about 1.4MW. Figure 1 and 2 show sample load profile curves for an individual community option and the central power plant option; and Table 1 shows the energy usage pattern for the inhabitants of Forcados Community. This usage pattern was obtained from oral explanations of how they use the appliances they have, coupled with the types of appliances used per household, and the number of households in the community. Since the load usage pattern of all rural coastline communities in Delta state is similar, it is assumed that the load profile and usage pattern for each of the other six communities around the Forcados River area will be similar to that of Forcados community, the only difference being the magnitude of the load per time.

Time of Day	Load in KW
-	
1.00	209.75
2.00	209.75
3.00	209.75
4.00	209.75
5.00	559.33
6.00	1,136.14
7.00	1,747.91
8.00	1,573.12
9.00	1,083.70
10.00	1,048.75
11.00	1,048.75
12.00	734.12
13.00	908.91
14.00	1,048.75
15.00	1,048.75
16.00	1,048.75
17.00	873.96
18.00	873.96
19.00	891.43
20.00	769.08
21.00	769.08
22.00	559.33
23.00	209.75
24.00	209.75

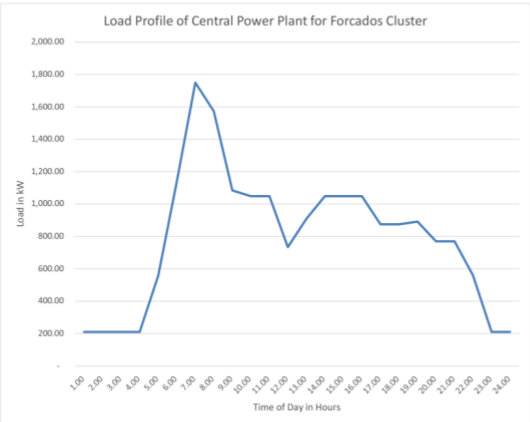

Figure 1: Estimated Load Profile for Central Power Plant for seven Coastline Communities around the Forcados River [17].

Time of Day	Load in KW
1.00	5.94
2.00	5.94
3.00	5.94
4.00	5.94
5.00	15.83
6.00	49.46
7.00	39.57
8.00	38.09
9.00	30.67
10.00	29.68
11.00	29.68
12.00	20.77
13.00	25.72
14.00	29.68
15.00	29.68
16.00	29.68
17.00	24.73
18.00	24.73
19.00	25.23
20.00	21.76
21.00	21.76
22.00	15.83
23.00	5.94
24.00	5.94

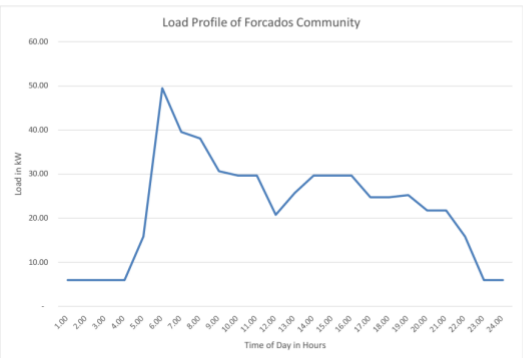

Figure 2: Estimated Load Profile of Forcados Community as a sample load profile for each of the seven Coastline Communities around the Forcados River.

Table 1: Estimated Load Profile and Usage Pattern of Forcados Community over a typical 24-hour period with peak load of 49.46kW [17]

SUMMARY LOAD PROFILE OF FORCADOS COMMUNITY

Time Bracket	DOMESTIC LOADS (kW)	RELIGIOUS LOADS (kW)	PUBLIC LOADS (kW)	COMM-ERCIAL LOADS (kW)	TOTAL LOADS (kW)
0:00 - 1:00	2		2	1.94	5.94
1:00 - 2:00	2		2	1.94	5.94
2:00 - 3:00	2		2	1.94	5.94
3:00 - 4:00	2		2	1.94	5.94
4:00 - 5:00	11.89		2	1.94	15.83
5:00 - 6:00	45.52		2	1.94	49.46
6:00 - 7:00	35.63		2	1.94	39.57
7:00 - 8:00	34.15		2	1.94	38.09
8:00 - 9:00	4	4	3	19.67	30.67
9:00 - 10:00	4	4	4	17.68	29.68
10:00 -11:00	4	4	4	17.68	29.68
11:00 - 12:00	4	4	4	8.77	20.77
12:00 - 13:00	4	2	2	17.72	25.72
13:00 - 14:00	4	4	3	18.68	29.68
14:00 - 15:00	4	4	4	17.68	29.68
15:00 - 16:00	4	4	4	17.68	29.68
16:00 - 17:00	4	4	4	12.73	24.73
17:00 - 18:00	4	4	4	12.73	24.73
18:00 - 19:00	4	1	2	18.23	25.23
19:00 - 20:00	4		2	15.76	21.76
20:00 - 21:00	3		2	16.76	21.76
21:00 - 22:00	2		2	11.83	15.83
22:00 - 23:00	2		2	1.94	5.94
23:00 - 24:00	2		2	1.94	5.94

5. Estimated Load Profiles of the Coastal Communities around the Benin River

This study considers twenty-three out of the numerous coastline communities around the Benin River area of Delta State in southern Nigeria. Figures 3 and 4 show sample load profile curves for the central power plant option and an individual community option for Ugegbe community, again obtained from oral interviews with the residents concerning the type and usage pattern of the appliances they have in their households, coupled with the number of households in the community. Since the load usage pattern of all rural coastline communities in Delta state is similar, it is assumed that the load profile and usage pattern for each of the other twenty-two communities around the Benin River area will be similar to that of Ugegbe community, the only difference being the magnitude of the load per time.

Time of Day	Load in KW
1.00	204.05
2.00	204.05
3.00	204.05
4.00	204.05
5.00	204.05
6.00	629.17
7.00	680.18
8.00	816.22
9.00	731.19
10.00	646.17
11.00	595.16
12.00	901.24
13.00	510.14
14.00	1122.30
15.00	1105.29
16.00	595.16
17.00	1479.39
18.00	1479.39
19.00	1479.39
20.00	1700.45
21.00	1700.45
22.00	850.23
23.00	204.05
24.00	204.05

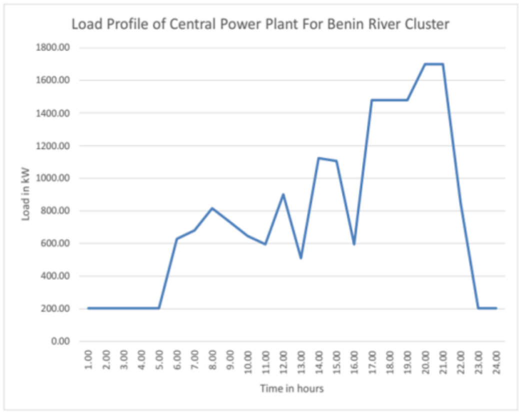

Figure 3: Estimated Load Profile for Central Power Plant for 23 Coastline Communities around the Benin River.

Time of Day	Load in KW
1.00	1.17
2.00	1.17
3.00	1.17
4.00	1.17
5.00	1.17
6.00	1.17
7.00	6.34
8.00	9.16
9.00	10.10
10.00	11.27
11.00	8.22
12.00	12.44
13.00	7.04
14.00	15.50
15.00	15.26
16.00	8.22
17.00	20.43
18.00	20.43
19.00	20.43
20.00	23.48
21.00	23.48
22.00	11.74
23.00	1.17
24.00	1.17

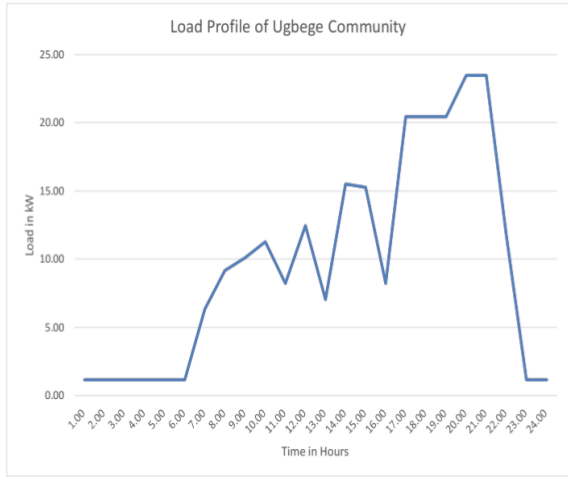

Figure 4: Estimated Load Profile of Ugbege Community as a sample load profile for each the 23 Coastline Communities around the Benin River.

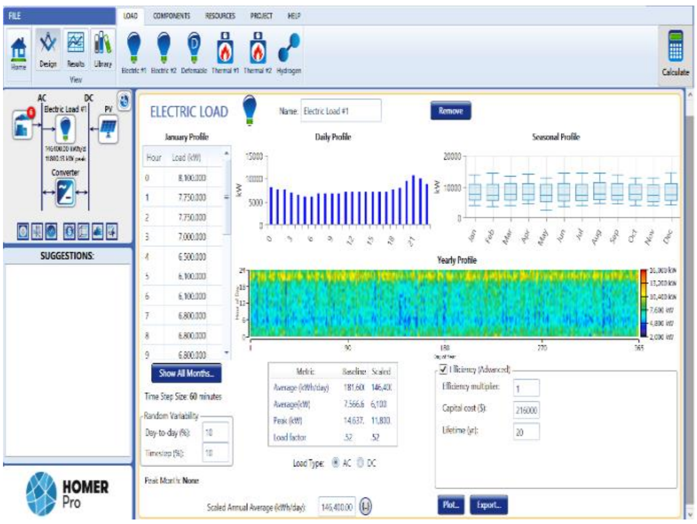

Figure 5: Load profile inputs for the proposed central power plant and microgrid at Escravos Cluster area

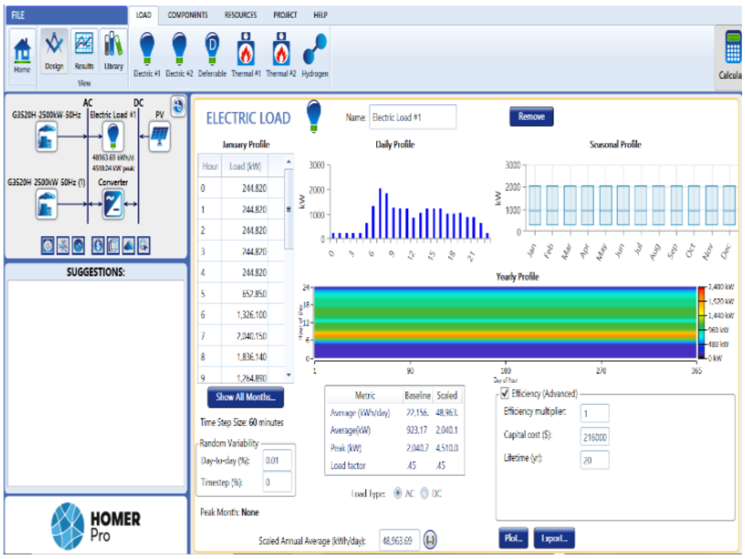

Figure 6: Load profile inputs for the proposed central power plant and microgrid a Forcados cluster area

Figure 7: Load profile inputs for the proposed central power plant and microgrid at Benin River cluster area

The optimization of inputs of the hybrid system based on the electricity load inputs for the three coastline areas are shown in Figures 5 to 7, for the central power plant options for Escravos, Forcados and Benin River in HOMER environment.

6. Configuration of the Proposed Hybrid Energy System.

The proposed configuration of the autonomous hybrid microgrids for the coastline areas of Escravos River, Forcados River and Benin River in Delta State, is a series-parallel hybrid configuration. The design philosophy is such that uninterrupted power supply is achieved, whether the central power plant option is used, or whether the option of having autonomous microgrids in each community is adopted instead.

7. Evaluation of the Study Performance

The results of the simulation of the optimal electricity solutions for the coastline areas of Delta state are presented for the Escravos, Forcados and Benin River Cluster areas in Tables 2 to 4. The base case scenario is the use of a natural gas generator power plant. This is because the area has an abundance of natural gas which has constituted an environmental menace due to constant flaring. This base case applies to both the central power plant scenario and the autonomous community scenario. It should be noted that, upon application of the parameters of the Weibull Distribution Function [19]to wind data obtained for the study area, it was discovered that the wind power density was about 89.27W/m2, at 50m hub height.

For a site to be considered viable for wind power generation, this value should be at least 500 W/m2 [20]. As a result of this, wind was not considered a viable contributor to the proposed energy mix for the study area.

The optimized solution considers the Cost of Electricity (COE) when the cost of the gas generation is factored in and when it is not factored in. HOMER optimized the different solutions based on the lowest Net Present Cost (NPC) and COE, and generated a set of results.

The solution of lowest net present cost is presented first on the optimization list as the winning system configuration, while the other systems with higher NPC and COE are presented below in increasing order. In simulating these system configurations, cost of gas fuel at $0.3/m3, operation and maintenance cost of gas power plant at $0.01/kW/operating hour, 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: Simulation results for a Central Power Plant and Autonomous Hybrid Energy System in each of the Communities in the Escravos Cluster Area.

S/N	NAME OF COMMUNITY	OPTIMAL SYSTEM CONFIGURATION (kW) Solar PV	Gas Generator	Li-Ion Battery	Con-verter	NPC Optimal System (US$)	COE Base Case (full) in US$	COE Base Case (without Gas gen Cost) in US$	COE Optimal System (FULL) in US$	COE Optimal System (Without Gas gen cost) in US$	ANNUAL FUEL COST (US$/yr)	ANNUAL SYSTEM ELECTRICITY PRODUCTION (kWh/yr)
1	Ugbuegungun		250.00	1,305.00	171.73	1,540,452.00	0.25	0.18	0.18	0.12	77,912.47	1,039,358.00
2	Costain		725.00	4,260.00	457.19	4,979,933.00	0.18	0.12	0.15	0.10	263,695.80	2,787,981.00
3	Arunton		2,500.00	8,036.00	1,218.19	15,061,990.00	0.14	0.09	0.12	0.07	730,105.40	10,406,460.00
4	Saharabubowei (I & I)		160.00	716.00	82.40	1,158,806.00	0.25	0.19	0.13	0.09	39,311.97	509,120.80
5	Kokodiagbene		1,000.00	3,598.00	660.15	6,118,976.00	0.15	0.10	0.13	0.08	303,678.20	3,994,847.00
6	Pepeama		360.00	1,142.00	170.40	2,419,586.00	0.16	0.10	0.13	0.08	109,449.80	1,454,692.00
7	Okerenkoko		1,000.00	4,632.00	593.30	5,654,646.00	0.17	0.10	0.13	0.08	275,020.80	3,647,217.00
8	Ogidigben		3,000.00	15,183.00	2,049.89	29,519,890.00	0.26	0.14	0.20	0.13	1,424,237.00	12,390,510.00
9	Akpakpa - Ajudaibo		1,000.00	6,154.00	635.39	5,939,053.00	0.16	0.10	0.13	0.08	291,552.10	3,863,990.00
10	Madagho		776.00	3,957.00	448.91	4,982,797.00	0.16	0.09	0.13	0.08	232,156.40	3,227,799.00
11	Kpokpo	54.66		786.00	15.80	156,445.80	0.97	0.41	0.27	0.27	-	68,095.77
12	Okpelama		550.00	1,357.00	214.84	3,071,421.00	0.17	0.12	0.14	0.09	141,789.90	1,831,763.00
13	Itebijaw		360.00	843.00	136.60	2,151,161.00	0.19	0.12	0.15	0.08	89,934.21	1,169,821.00
14	Opuedebubor		420.00	1,275.00	195.95	2,873,637.00	0.17	0.11	0.14	0.08	129,503.60	1,673,655.00
15	Ijaghala		250.00	649.00	104.24	1,696,883.00	0.19	0.11	0.15	0.09	68,383.50	884,053.90
16	Oporoza		3,944.00	8,208.00	1,344.05	31,750,250.00	0.13	0.08	0.11	0.08	1,742,703.00	22,317,100.00
17	Azama		250.00	822.00	122.40	1,848,191.00	0.17	0.10	0.14	0.08	79,409.66	1,046,315.00
18	Inikrougha		360.00	1,374.00	183.40	2,070,654.00	0.20	0.12	0.15	0.09	84,778.27	1,138,577.00
19	Ubafan		160.00	1,019.00	89.99	1,208,692.00	0.23	0.12	0.18	0.09	42,585.88	553,662.40
20	Kunuknuma		725.00	3,978.00	438.06	5,417,328.00	0.17	0.12	0.14	0.10	293,149.30	3,095,667.00
21	Kurutie		854.00	4,361.00	494.68	5,422,261.00	0.16	0.09	0.12	0.08	250,722.90	3,558,148.00
22	Camp 5	119.21	60.00	1,251.00	49.57	572,813.60	0.45	0.17	0.24	0.14	7,459.69	204,863.00
23	Ugbologin		776.00	3,969.00	449.79	4,991,681.00	0.16	0.09	0.13	0.08	232,804.60	3,238,149.00
24	Ajudaibo		1,000.00	6,154.00	635.39	5,939,053.00	0.16	0.10	0.13	0.08	291,552.10	3,863,990.00
25	Seashore		550.00	1,027.00	185.81	3,467,231.00	0.15	0.10	0.12	0.08	171,255.00	2,224,943.00
26	Ajoguda		420.00	1,225.00	201.00	2,898,908.00	0.17	0.11	0.14	0.08	131,304.20	1,699,806.00
	Total for Communities		20,480.00			146,546,600.40					7,201,896.55	87,965,834.87
	Average for Communities						0.22	0.13	0.15	0.10		
	CPP Escravos		12,132.00			74,866,250.00	0.11	0.08	0.11	0.08	4,113,318.00	53,535,830.00

Table 3: Simulation results for a Central Power Plant and Autonomous Hybrid Energy Systems in each of the Communities in the Forcados Cluster Area.

S/N	NAME OF COMMUNITY	OPTIMAL SYSTEM CONFIGURATION (kW) Solar PV	Gas Generator	Li-Ion Battery	Con-verter	NPC Optimal System (US$)	COE Base Case (full) in US$	COE Base Case (without Gasgen Cost) in US$	COE Optimal System (FULL) in US$	COE Optimal System (Without Gasgen cost) in US$	ANNUAL FUEL COST (US$/yr)	ANNUAL SYSTEM ELECTRICITY PRODUCTION (kWh/yr)
1	Forcados		160.00	937.00	71.63	1,203,823.00	0.23	0.12	0.18	0.09	42,575.47	549,150.80
2	Ogulagha		1,500.00	8,386.00	683.79	7,654,117.00	0.16	0.09	0.13	0.08	356,280.20	5,040,948.00
3	Yeye		420.00	2,327.00	212.28	2,807,887.00	0.17	0.11	0.14	0.09	125,035.50	1,640,641.00
4	Burutu		2,500.00	13,471.00	1,093.93	12,492,590.00	0.16	0.09	0.13	0.08	575,075.40	8,231,257.00
5	Odimodi		550.00	2,549.00	230.25	2,947,187.00	0.19	0.12	0.14	0.09	133,624.70	1,766,475.00
6	Sekebolou		420.00	2,411.00	183.75	2,566,666.00	0.20	0.12	0.15	0.09	108,260.50	1,412,945.00
7	Yokri		250.00	1,465.00	109.88	1,622,388.00	0.21	0.12	0.16	0.09	63,656.09	842,703.40
	Total for Communities		5,800.00			31,294,658.00					1,404,507.86	19,484,120.20
	Average for Communities						0.19	0.11	0.15	0.09		
	CPP Forcados	5,000.00				8,971,790.00	0.13	0.08	0.13	0.08	1,351,104.70	18,603,126.00

Table 4: Simulation results for a Central Power Plant and Autonomous Hybrid Energy Systems in each of the Communities in the Benin River Cluster Area.

S/N	NAME OF COMMUNITY	OPTIMAL SYSTEM CONFIGURATION (kW) Solar PV	Gas Generator	Li-Ion Battery	Con-verter	NPC Optimal System (US$)	COE Base Case (full) in US$	COE Base Case (without Gasgen Cost) in US$	COE Optimal System (FULL) in US$	COE Optimal System (Without Gasgen cost) in US$	ANNUAL FUEL COST (US$/yr)	ANNUAL SYSTEM ELECTRICITY PRODUCTION (kWh/yr)
1	Ugbege		100.00	437.00	48.96	776,154.40	0.37	0.19	0.25	0.10	22,857.11	262,147.30
2	Ekekporo		160.00	708.00	80.40	1,161,008.00	0.25	0.14	0.19	0.09	39,625.64	513,475.20
3	Agogboro		1,000.00	3,518.00	438.64	4,935,225.00	0.19	0.12	0.14	0.09	228,072.90	2,996,528.00
4	Ogheye-Dimigun		776.00	4,113.00	389.01	4,153,657.00	0.19	0.11	0.13	0.08	183,777.10	2,561,745.00
5	Ogheye-Eghor		420.00	1,791.00	187.23	2,419,901.00	0.22	0.14	0.16	0.09	98,302.30	1,284,211.00
6	Orere		550.00	2,012.00	250.53	2,872,091.00	0.20	0.13	0.14	0.09	128,678.40	1,712,282.00
7	Ugogegin		420.00	1,791.00	187.23	2,419,901.00	0.22	0.14	0.16	0.09	98,302.30	1,284,211.00
8	Atsuran		100.00	428.00	43.33	877,326.50	0.29	0.15	0.21	0.10	29,714.44	339,030.50
9	Bobi		100.00	764.00	45.80	850,247.60	0.31	0.16	0.22	0.10	27,774.00	319,676.00
10	Bateren		100.00	428.00	43.33	877,326.50	0.29	0.15	0.21	0.10	29,714.44	339,030.50
11	Deghele		100.00	428.00	43.33	877,326.50	0.29	0.15	0.21	0.10	29,714.44	339,030.50
12	Gbogbodu		100.00	500.00	47.10	825,243.30	0.32	0.17	0.23	0.10	26,192.51	301,032.20
13	Jakpa		170.00	882.00	81.72	1,178,919.00	0.24	0.15	0.18	0.10	46,922.55	555,015.10
14	Aja-Amita		160.00	708.00	80.40	1,161,008.00	0.25	0.14	0.19	0.09	39,625.64	513,475.20
15	Gbokoda		550.00	2,781.00	238.15	2,705,349.00	0.21	0.14	0.15	0.09	116,803.20	1,554,203.00
16	Ebrohimi		100.00	500.00	47.10	825,243.30	0.32	0.17	0.23	0.10	26,192.51	301,032.20
17	Adagbrassa		100.00	500.00	47.10	825,243.30	0.32	0.17	0.23	0.10	26,192.51	301,032.20
18	Dudu Town		160.00	542.00	66.05	1,069,919.00	0.30	0.16	0.21	0.09	33,614.62	432,656.40
19	Idebagbene		100.00	428.00	43.33	877,326.50	0.29	0.15	0.21	0.10	29,714.44	339,030.50
20	Asabotie		160.00	542.00	66.05	1,069,919.00	0.30	0.16	0.21	0.09	33,614.62	432,656.40
21	Ureju		250.00	938.00	92.57	1,369,074.00	0.28	0.17	0.19	0.09	46,275.30	605,739.60
22	Young Town		360.00	1,737.00	159.81	1,952,711.00	0.23	0.14	0.16	0.09	77,129.99	1,035,008.00
23	Bresibi		100.00	500.00	47.10	825,243.30	0.32	0.17	0.23	0.10	26,192.51	301,032.20
	Total for Communities		6,136.00			36,905,363.20					1,445,003.47	18,623,280.00
	Average for Communities						0.27	0.15	0.19	0.09		
	CPP Benin River		5,000.00			29,169,640.00	0.13	0.08	0.13	0.08	1,393,465.50	18,276,027.00

8. Discussion of Findings

In this section, the results are discussed based on NPC, COE, Annual Fuel Costs and Annual Electricity. It is to be noted that the costs of the microgrids discussed in this section do not include the cost of the network lines and associated switchgear required for connecting the consumers to the power generation systems. These network system costs are usually borne by the intervention agencies as a subsidy to the microgrid system. The amounts considered in this study are in US dollars because all the major components of the system are sourced internationally and paid for in US dollars. Even the natural gas that is sourced in Nigeria is priced and paid for in US dollars.

The optimal system configuration based on the HOMER Pro Simulation results for majority of the communities along the coastline areas of Delta State is a combination of Gas Generator + Lithium-ion battery bank + Converter. The Lithium-ion battery bank serves to reduce the operating hours of the generator, which consequently reduces the cost of the fuel and maintenance of the generator. Only Kpokpo and Camp 5 Communities in Escravos Cluster area were recommended for a Solar PV-Battery- Converter hybrid system, as their load demand was so low that the Solar PV+ Battery Bank system could serve the loads at a lower cost than deploying gas generators.

8.1 Comparison of Optimized Configurations based on Net Present Cost (NPC)

Figure 8 shows the comparison of the NPC of the optimal hybrid system configurations for each of the communities in the Escravos cluster area, as well as the NPC for a proposed central power plant. The total NPC of all the individual microgrids in each of the communities for the Escravos Cluster area is about 146.55 million USD.

If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the NPC would be reduced by 49% to about 74.87 million USD. Hence, from the NPC point of view, the central power plant option is the most feasible solution for the provision of electricity for the coastline areas of Delta State around the Escravos River.

Figure 9 shows the comparison of the NPC of the optimal hybrid system configurations for each of the communities in the Forcados Cluster area, as well as the NPC for a proposed central power plant. The total NPC of all the individual microgrids in each of the communities for the Forcados Cluster area is about 31.29 million USD. If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the NPC would be reduced by 7% to about 28.97 million USD. Since the difference between the NPC of the two options is not that much, the option of providing an autonomous hybrid microgrid in each of the communities in the coastline areas of Delta state around the Forcados River area is preferred.

Figure 10 shows the comparison of the NPC of the optimal hybrid system configurations for each of the communities in the Benin River cluster area, as well as the NPC for a proposed central power plant. The total NPC of all the individual microgrids in each of the communities for the Escravos Cluster area is about 36.91 million USD. If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the NPC would be reduced by 21% to about 29.17 million USD. Hence, from the NPC point of view, the Central Power Plant option is the most feasible solution for the provision of electricity for the coastline areas of Delta State around the Benin River.

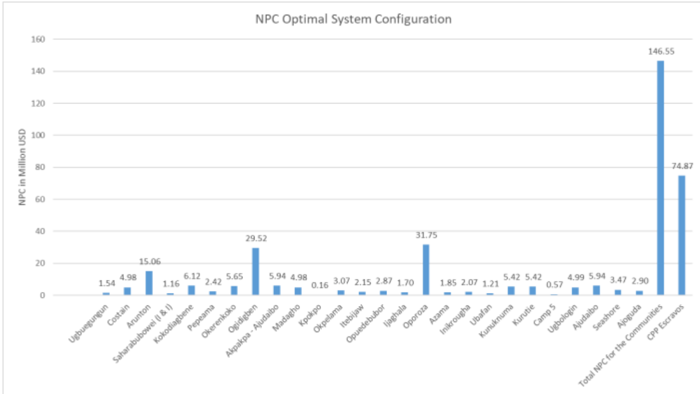

Figure 8: Comparison of the NPC of the Optimal System Configuration for each of the Communities and the Central Power Plant in Escravos Cluster Area

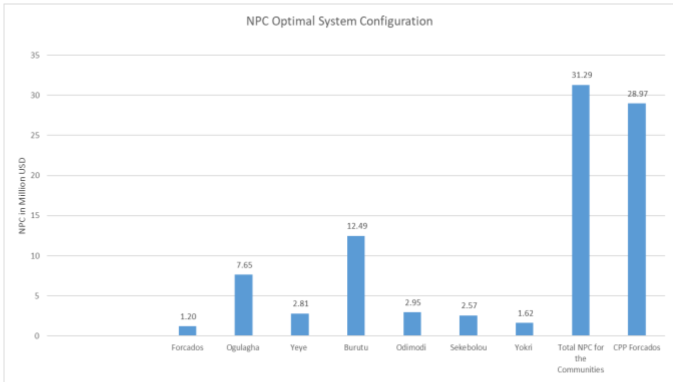

Figure 9: Comparison of the NPC of the Optimal System Configuration for each of the Communities and the Central Power Plant in Forcados Cluster

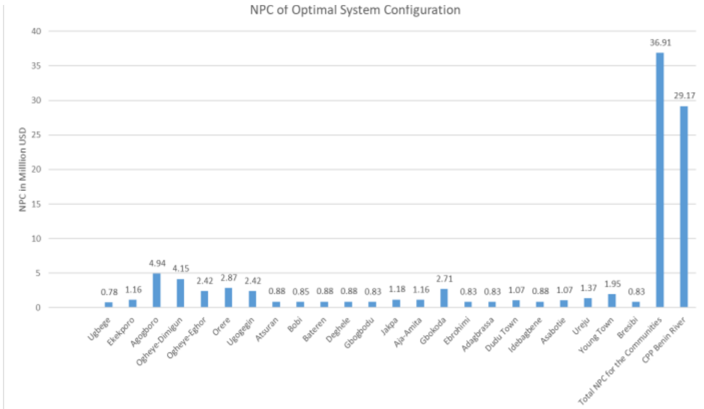

Figure 10: Comparison of the NPC of the Optimal System Configuration for each of the Communities and the Central Power Plant in Benin Cluster.

8.2 Comparison of Optimized Configurations based on Cost of Electricity (COE)

Figure 11 shows the comparison of the COE of the optimal hybrid system configurations for each of the communities in the Escravos Cluster area, the average COE for the communities, as well as the COE for a proposed central power plant. The average COE for the base case hybrid system configurations for all the microgrids in the Escravos Cluster area is about 0.22 USD/kWh, when the cost of the gas generator is considered. If the cost of the gas generator is treated as a grant or subsidy, the average base case COE is about 0.13 USD/kWh. In the case of the optimal hybrid system configuration, the COE is 0.15 USD/kWh, but if the cost of the gas generator is treated as a subsidy or grant, the COE drops to about 0.10 USD/kWh. In 14 out of the 26 communities considered in this area, the COE in this scenario actually drops to about 0.08USD/kWh. The sharp difference in the COE for Kpokpo community (they have the smallest population) at 0.97 USD/kWh is due to the fact that the load demand (about 5kW) did not justify the cost of the 30kW gas generator used in the base case simulation. HOMER therefore proposed an optimized renewable solution for this community consisting of a 55kW Solar PV with a 786kW battery bank, which yielded a much lower COE of 0.27 USD/kWh.

If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the COE would be 0.11 USD/kWh, and if the cost of the gas generator were to be treated as a grant or subsidy, the COE drops to about 0.08 USD/kWh. It is pertinent to note that, in these communities along the coastline areas of Delta State, willingness and ability to pay for electricity is usually challenge, hence the COE must be reduced to the barest minimum possible. Although the consumers may be reluctant to pay for the gas fuel, which they view as their birthright, the gas is not useable in its raw form, and must be processed before it can be used. The gas-processing operation and equipment costs money, and if they do not pay for the gas fuel, the operation of the microgrids may not continue when the Oil and Gas Companies/Operators move away from this area, either to offshore locations or to other coastline areas of Nigeria.

Hence, from the COE point of view, the CPP option is the most feasible solution for the provision of electricity for the coastline areas of Delta State around the Escravos River, having the lowest COE of about 0.08 USD/kWh which covers fuel and maintenance costs only. Any community around the Escravos River area that is not among the 26 communities considered in this study, can be powered by an autonomous hybrid microgrid similar to those in each of the 14 communities whose design achieved a lowest COE of 0.08 USD/kWh.

Similarly, Figure 12 shows the comparison of the COE of the optimal hybrid system configurations for each of the communities in the Forcados Cluster area, the average COE for the communities, as well as the COE for a proposed central power plant. The average COE for the base case hybrid system configurations for all the microgrids in the Forcados Cluster area is about 0.19 USD/kWh, when the cost of the gas generator is considered. If the cost of the gas generator is treated as a grant or subsidy, the average base case COE is about 0.11 USD/kWh. In the case of the optimal hybrid system configuration, the COE is 0.15 USD/kWh, but if the cost of the gas generator is treated as a subsidy or grant, the COE drops to about 0.09 USD/kWh. In Ogulagha and Burutu Communities (they have the biggest load demand), this COE is about 0.08 USD/kWh.

If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the COE would be 0.13 USD/kWh, and if the cost of the gas generator were to be treated as a grant or subsidy, the COE drops to about 0.08 USD/kWh. Hence, from the COE point of view, although the CPP option is the most feasible solution for the provision of electricity for the coastline areas of Delta State around the Forcados River, the autonomous hybrid microgrid system is the most feasible for Burutu and Ogulagha communities. The other communities could either have their own autonomous hybrid microgrid at a slightly higher COE of 0.09USD/kWh, or draw power from either of these two communities using a 33kV distribution network.

Figure 13 shows the comparison of the COE of the optimal hybrid system configurations for each of the communities in the Benin River Cluster area, the average COE for the communities, as well as the COE for a proposed central power plant. The average COE for the base case hybrid system configurations for all the microgrids in the Benin River cluster area is about 0.27 USD/kWh, when the cost of the gas generator is considered. If the cost of the gas generator is treated as a grant or subsidy, the average base case COE is about 0.15 USD/kWh. In the case of the optimal hybrid system configuration, the COE is 0.19 USD/kWh, but if the cost of the gas generator is treated as a subsidy or grant, the COE drops to about 0.09 USD/kWh. In Ogheye-Dimigun community only, this COE is about 0.08 USD/kWh. Others vary between 0.09 USD/kWh (11 out of 23 Communities) and 0.10 USD/kWh (11 out of 23 Communities).

If all these microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the COE would be 0.13 USD/kWh, and if the cost of the gas generator were to be treated as a grant or subsidy, the COE drops to about 0.08 USD/kWh.

The results obtained from this study seem to suggest that the bigger the capacity of the hybrid energy system, the lower the COE. The lowest COE for a hybrid energy system encountered in the literature reviewed in this research was observed from the work of Rehman and El-Amin (2016) [18]. The hybrid energy system designed by them, made up of 1,500kW solar PV array and 4 x 1,120kW diesel generators yielded a COE of USD 0.038/kWh. Hence, from the COE point of view, the CPP option is the most feasible solution for the provision of electricity for the coastline areas of Delta State around the Benin River. Converting this COE of 0.08 USD/kWh to Naira at the official exchange rate by the Central Bank of Nigeria of N448.05 yields an average local cost of electricity of N 35.84/kWh. This compares quite favorably with the average tariff of NGN 54.86 for a Residential Consumer residing within the service areas of the Benin Electricity Distribution Company (BEDC) for 2021 (which includes Delta State); as issued by the Nigerian Electricity Regulatory Commission (NERC), in the 2019 Minor Review of the Multi-Year Tariff Order (MYTO) of 2015, and Minimum Remittance Order for the year 2020.

This subsidized COE for the Coastline areas of Delta State should encourage them to embrace the productive use of electricity for socio-economic development, as well as act as an incentive to attract small to medium scale industries to be set up in these areas.

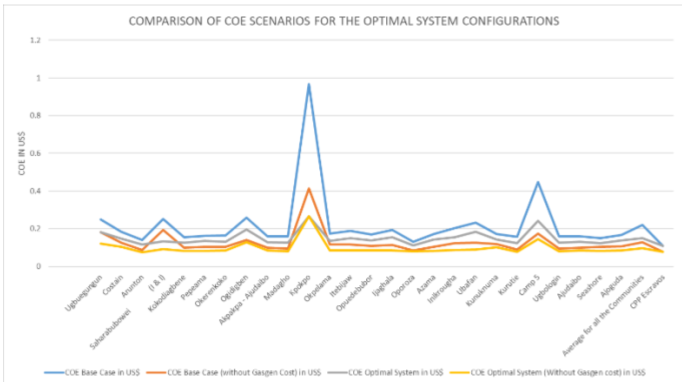

Figure 11: Comparison of the COE of the Optimal System Configuration for each of the Communities and the Central Power Plant in Escravos Cluster Area.

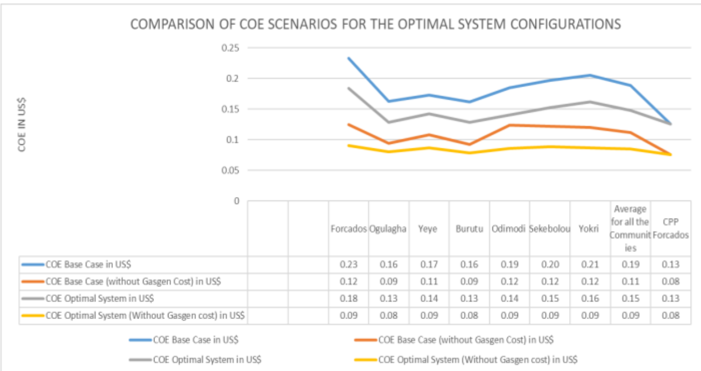

Figure 12: Comparison of the COE of the Optimal System Configuration for each of the Communities and the Central Power Plant in Forcados Cluster Area.

8.3 Comparison of Optimized Configurations based on Annual Fuel Cost

Figure 14 shows the comparison of the annual fuel cost of the optimal hybrid system configurations for each of the communities in the Escravos cluster area, the total annual fuel costs for all the communities, as well as the annual fuel cost for a proposed central power plant.

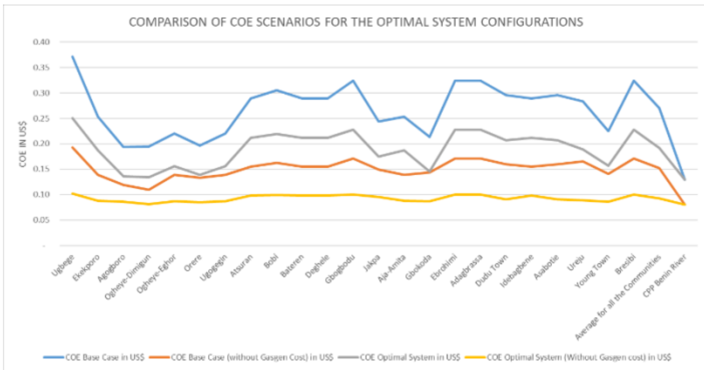

Figure 13: Comparison of the COE of the Optimal System Configuration for each of the Communities and the Central Power Plant in Benin River Cluster Area.

The fuel type considered for use in this study is is Natural Gas fuel, which can be compressed and transported by boat to the microgrid location for use in the generator. Using natural gas instead of diesel can cut electricity generation costs by up to 50%, while mitigating the harmful effects of gas flaring, which is prevalent in the Coastline areas of Delta State, hence it is recommended for use in this area. The total annual fuel cost for the optimal hybrid system configurations for the microgrids in 26 communities of the Escravos Cluster area amounts to about 7.2 million USD. If these 26 microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the total annual fuel cost would drop by about 43% to about 4.11 million USD.

In the case of the Forcados River area, the total annual fuel cost for the optimal hybrid system configurations for the microgrids in 7 communities of the Forcados Cluster area amounts to about 1.4 million USD, as shown in Figure 15. If these 7 microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the total annual fuel cost would drop by about 4% to about 1.35 million USD. Since the difference is annual fuel costs is quite small, the results support the adoption of individual microgrids in each of the communities in this area.

The results for the Benin River Cluster area shown in Figure 16, indicate that the total annual fuel cost for the optimal hybrid system configurations for the microgrids in 23 communities amounts to about 1.45 million USD. If these 23 microgrids were to be replaced with one central microgrid generating and radiating power to each of the communities on a 33kV distribution network, the total annual fuel cost would drop by about 4% to about 1.39 million USD. Since the difference in fuel costs for the Central Microgrid and Individual Community Microgrid scenarios is quite small, other factors such as NPC and COE will need to be considered in order to determine the most feasible option in this area.

8.4 Comparison of Optimized Configurations based on Annual Electricity Production

The annual electricity production of any given system is the total electricity produced by the system in one year.

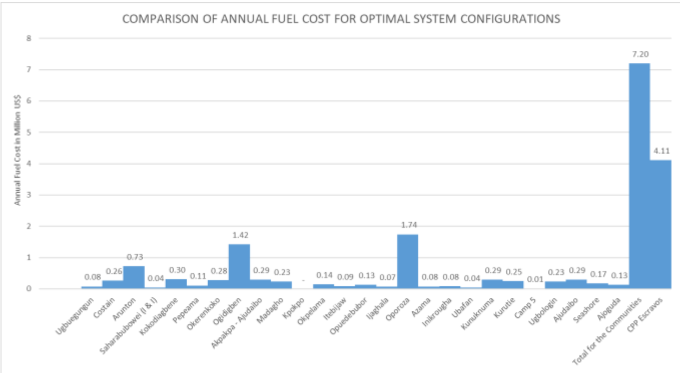

Figure 14: Comparison of the Annual Fuel Cost of the Optimal System Configuration for each of the Communities and the Central Power Plant in Escravos Cluster Area

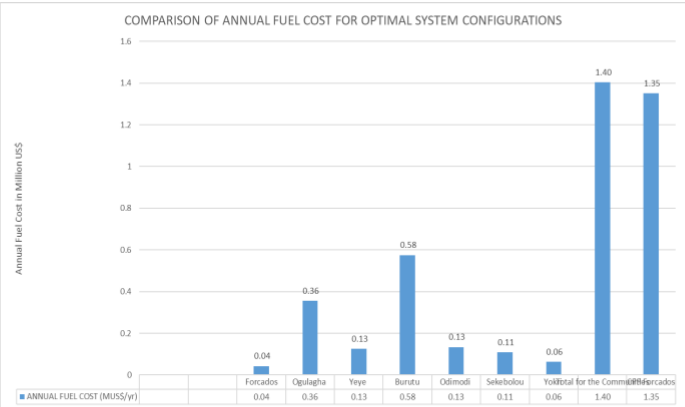

Figure 15: Comparison of the Annual Fuel Cost of the Optimal System Configuration for each of the Communities and the Central Power Plant in Forcados Cluster Area.

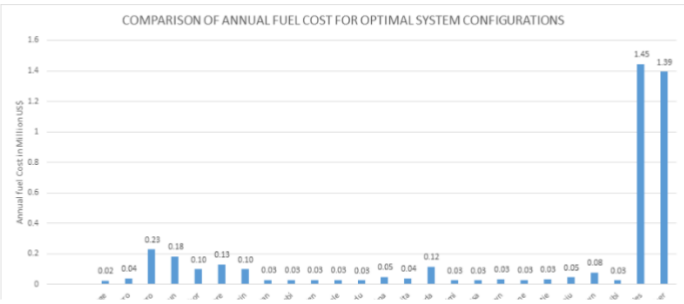

Figure 16: Comparison of the Annual Fuel Cost of the Optimal System Configuration for each of the Communities and the Central Power Plant in Benin River Cluster Area

Figure 17 shows the total annual electricity production for the communities in the Escravos River area, their individual electricity production, and the annual electricity production for the Central Microgrid (CPP) scenario. The results show that the total annual electricity production for the 26 communities in this area is about 87.97GWh in one year, while the electricity produced by the proposed central power plant is about 53.54GWh.

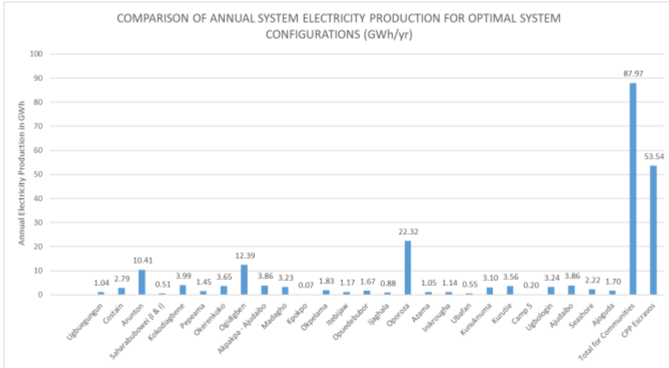

Figure 17: Comparison of the Annual Electricity Production of the Optimal System Configuration for each of the Communities and the Central Power Plant in Escravos

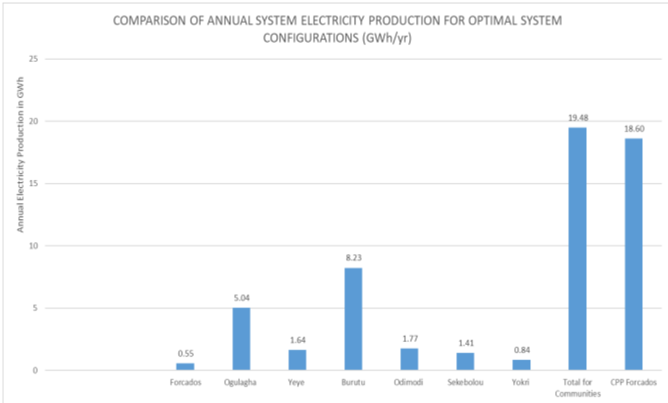

Figure 18: Comparison of the Annual Electricity Production of the Optimal System Configuration for each of the Communities and the Central Power Plant in Forcados

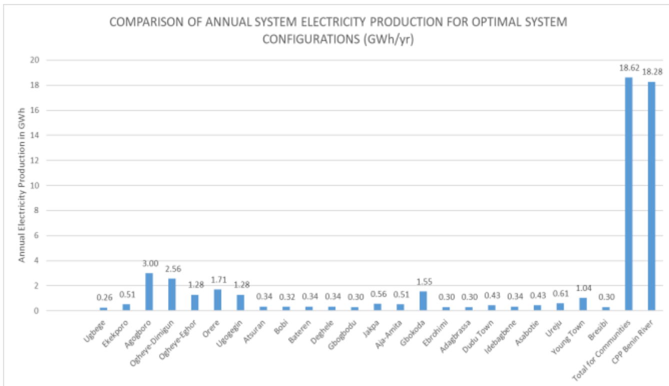

Figure 19: Comparison of the Annual Electricity Production of the Optimal System Configuration for each of the Communities and the Central Power Plant in Benin River

This seems to favour the autonomous microgrid option for each community. Similarly, Figure 18 shows that the total annual electricity production for the 7 communities in the Forcados River Cluster area is about 19.48 GWh in one year, while the electricity produced by the proposed central power plant is about 18.60GWh. Again, the option of setting up an autonomous microgrid in each of the communities is supported by this result. From Figure 19, the total annual electricity production for the 23 communities in the Benin River Cluster area is about 18.62 GWh in one year, while the electricity produced by the proposed central power plant is about 18.28GWh. There is not much difference between the two options in this regard, thus the decision will need to depend on other variables like the NPC and COE.

8.5 Selected Scenario Based on Optimized Results

From the analysis of the Hybrid Energy System Configurations for the communities considered in the Coastline area of Delta State, the 12MW, natural gas-fueled autonomous central microgrid option is best for the twenty-six communities around the Escravos River. The 5MW, natural gas-fueled autonomous central microgrid option is also recommended for the twent-three communities along the Benin River area. However, autonomous hybrid microgrid systems in each of the seven communities considered in the Forcados River area is the best solution, based on the optimization results of NPC, COE, Annual Fuel Costs and Annual Electricity production, all taken together.

9. Conclusions and Future Directions

This paper investigated the harnessing of solar and wind power hybrid energy system in coastline communities of southern Nigeria as part of sustainable development. The data of the available solar and wind potential of the coastline communities along the Benin River, Escravos River and Forcados River were obtained in this study, and evaluated based on mathematical models using the HOMER software.
The electricity needs of any community along the coastline areas of Delta State can be met with the design, simulation and construction of an autonomous hybrid microgrid either as a central arrangement for a cluster of communities, or as an individual arrangement for each community. The central microgrid arrangement is recommended for the twenty-six communities around the Escravos River and twenty-three communities around the Benin River. This option provides the opportunity of the lowest COE at 0.08 USD/kWh or approximately NGN 36/kWh, assuming that the cost of the power plant and distribution network infrastructure up to metering, is donated by an intervention agency, whether government or private.

The individual community microgrid arrangement is recommend for the seven communities around the Forcados River. This arrangement provides the opportunity of energy independence from disruptions that could be caused by incidents of vandalism, community unrest or natural disasters in the other communities along the line route of the 33kV line coming from the central power station. Unfortunately, this energy independence comes at a slightly higher COE of about 0.09 - 0.10 USD/kWh.

The advantage of using the HOMER optimization tool for the design and simulation of these Hybrid Energy Systems is that, the software provides other useful information that aids business decision making, such as providing other system configuration options and their cost implications over the life of the equipment.

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