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Economic Analysis of Anaerobic Digestion-Powered Engines and Solar PV Hybrid Systems for Sustainable Energy in Obeagu Community

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ABSTRACT: The economic challenges faced by the Obeagu community in Enugu South Local Government Area of Enugu State, Nigeria, due to the reliance on diesel-powered electricity—due to inadequate national grid supply—have led to the exploration of a hybrid electricity system. This system combines solar PV and anaerobic digestion-based internal combustion engines to reduce the financial burden. To evaluate the economic feasibility of this solution, MATLAB, Excel, HOMER Pro software, and accounting tools were used, incorporating local solar potential data and the daily waste generation rate. The economic assessment revealed that the proposed hybrid system, requiring an initial capital investment of $674,128, achieves a favourable Net Present Value (NPV) of $33,932, with an Internal Rate of Return (IRR) of 17.9% and a Return on Investment (ROI) of 16.2%. These values demonstrate that the hybrid system is economically viable compared to a grid-supported diesel generator. Furthermore, the system's estimated cost of energy (COE) of 0.246 $/kWh is lower than the reviewed literature average of 0.30 $/kWh for the diesel engine-based alternative preferred by the Obeagu settlement. Given these economic benefits, it is recommended that technocrats, government bodies, and entrepreneurs invest in this proposal to alleviate the community's economic strain.

KEYWORDS: Alternative energy, Waste to Energy, Hybrid Systems

I. INTRODUCTION

The centralized electricity system in Nigeria relies largely on natural gas power plants (86%) and large hydropower facilities (14%), but challenges in resource availability, aging equipment, and inefficiencies in transmission have limited operational effectiveness. [1]asserted that gas turbines constitute much over 60% of the total number of electricity generating sets in the facility of Power Holding Company of Nigeria, PHCN, the other number of major means of electricity generating sets being by the use of steam and hydro turbines and various renewable energy forms. While urban areas enjoy a higher grid connection rate of 80%, only 34% of underdeveloped regions have access to electricity [2]. With an electricity access rate of just about 59.5% as of 2021. Nigeria lags behind comparable nations like Egypt and South Africa, which generate significantly more electricity per capita despite having smaller populations [3].

Amidst these challenges, waste-to-energy (WtE) technologies present a promising solution for addressing waste management issues while simultaneously generating renewable energy. WtE encompasses various methods, including thermochemical, physicochemical, and biochemical processes, to convert waste materials into usable energy [4]. Anaerobic digestion, a biochemical process, is particularly effective for converting organic waste into biogas, which can be utilized for electricity generation.

Pig farming in Nigeria, is sufficiently contributing to the agricultural sector through large quantity of excreta from the pigs which most times are dumped off indiscriminately resulting to risks to public health and pollution to the environment. This discarded piggery waste forms a reasonable quantity of un-tapped renewable energy resource for production of energy and other utilisable potentials. This could be made possible through employing

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anaerobic digestion system such that biogas generated from it could be used to generate electricity thereby making available effective waste management and electric energy challenge solutions. Given the abundance of piggery waste in Nigeria, this research seeks to explore its potential for electricity generation through anaerobic digestion-powered engines, integrated with solar photovoltaic (PV) systems for hybrid power solutions. With a population of about 1200 people judging from an average of 6 per household that is about 200 household as stated by [5], the study location, Obeagu piggery settlement known for its massive piggery farming has health centres schools and shops and generates great volume of organic waste. This settlement suffers frequent electricity challenges and augments the national grid with generating sets powered mainly by diesel engines as preferred alternative [6]. [7]in their work, unit cost of electricity in Nigeria: a cost model for diesel-powered generating system asserted that cost of energy (COE) of diesel-powered generating system stood at an average of 0.30 $/kWh. This made it an ideal candidate to evaluate the economic feasibility of a sustainable renewable hybrid energy system that addresses the community's electricity induced financial challenges.

II. LITERATURE REVIEW

There has been notable public and governmental focus on hybrid renewable and waste-to-energy (WtE) technologies as a response to mounting concerns surrounding emission from fossil fuels use, conventional waste management methods and the imperative to enhance resource recuperation from waste streams. Consequently, HRE and waste-to-energy technologieshave emerged as a promising solution, integrating multiple inexhaustible energy sources [8].

This combination of inexhaustible and WtE system in a hybrid mode brings about several benefits, including enhanced energy storage capacity, reduced generation costs, improved energy quality, and overall heightened energy efficiency when compared to single-source systems [8]; [9]. Hybrid systems facilitate smoother circulation and distribution, mitigate the risk of line and transformer incidents, elevate control standards, and lessen environmental impacts. Consequently, these systems bolster the overall reliability of viable energy setups [8];[9].

[10]asserted that in the consumption rate of different energy sources in Nigeria, fuel wood has highest percentage of 67, petroleum has 22, natural gas has 10 while the least is hydro with just 1. Waste-to-energy (WtE) showed zero percentage implying that in Nigeria, the necessary attention has not been given towards that direction. This is clearly shown in figure 1.

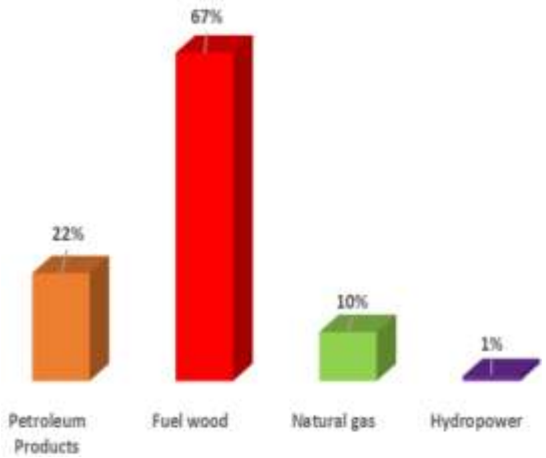

Fig. 1Consumption rate of different Energy sources in Nigeria [10].

As it ensures use of energy that is more efficient and less pollution production, hybrid of biogas-based and solar- PV module system connected to the grid could play a very crucial role to meet both the future and present electricity demand for Nigeria and any other state. The benefits by the installation of solar PV systems alone have been demonstrated by earlier researchers where it was asserted that a profitable positive Net Present Value (NPV) was attained to the tune of $5,186 in Enugu, the area under study, $7,156 in Kano, and $7,038 [11]. [6] had estimated the load demand for the pig ranches and considered households at Obeagu community at 435.99 MWh/year or 435,992.5 kWh/year (1,194,500 Wh/d) while analysing only the techno implications of installing hybrid of Anaerobic Digestion Engines and Solar PV in the area.

In summary from the literature survey, it is evident that in the context of Obeagu, the assessment of economic potentials of hybrid of solar photovoltaic (PV) and anaerobic digestion-based internal combustion engines powered by Waste-to-energy (WtE) has not been done. The forms the research gap hence the need for economic appraisal of the proposed hybrid towards curbing electric power challenges in the area.

III. MATERIALS AND METHOD.

Research Distinct Stages.

A field study followed by a feasibility study and subsequently hybrid system design are three distinct stages carried out for the adopted methodology of the research using MATLAB and

HOMER Pro. Briefly, the overview of the three steps is evident in figure 2.

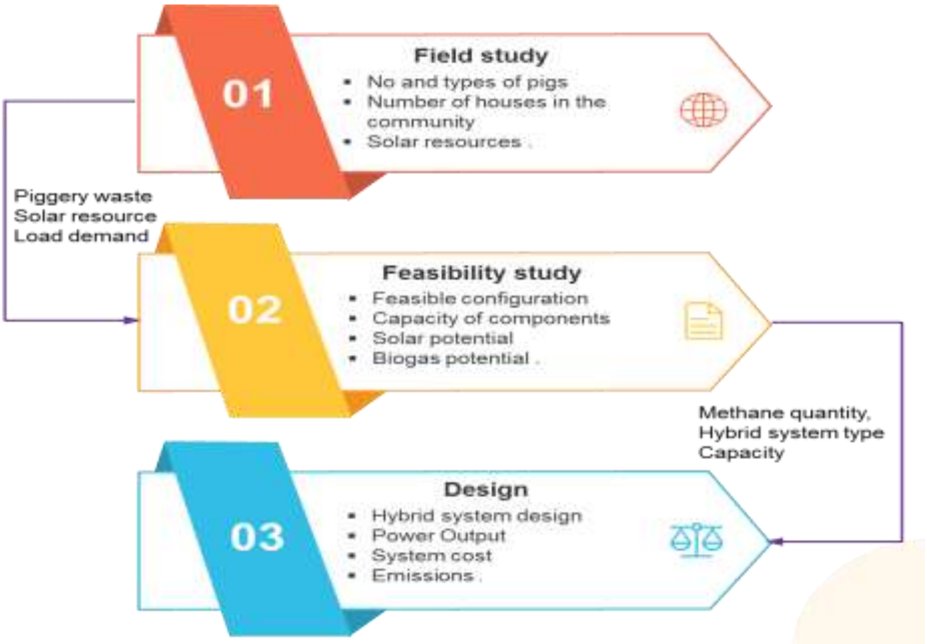

Fig. 2: Stages of execution of the methodology.

Geographical Location of study area.

Situated at coordinates 6°24′N 7°30′E with an average annual temperature of 27°C and 69% humidity, Obeagu community is in Enugu South Local Government Area (LGA) of Enugu State, Nigeria. The LGA has a land area of 67 km² and a population of 198,032 resulting to a high population density of 3,990/km². Located near Nyama river as known by the locals for the obvious need of water for its operation, the pig ranch has two phases in full operation the third phase is being developed. Figure 3clearly shows the location of the study area.

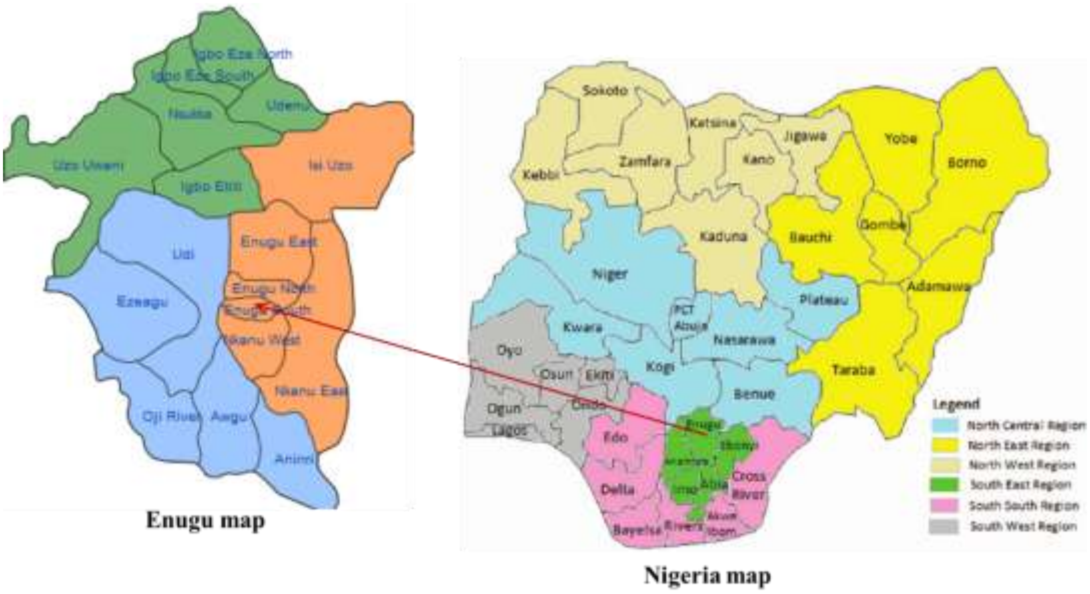

Fig. 3: Nigeria map housing Enugu state map and Enugu South LGA map containing Obeagu.

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Piggery Activities and Waste Generation.

Approximately 150 farms, each having an average of 40-60 pigs made up of boars, sows, piglets and dams are found in the pig ranch. Excreta and waste water generate constitute the waste and it varies with the population of each farm. The distribution of pigs across with a total of 600 animals is presented in Table 1. The volume of waste generatable from this population according to reviewed documents relating to hybrid power systems offers great biogas production which can be converted to renewable energy.

Table 1: Distribution of Pigs quantified in the farm.

Type	Number
Boar	165
Dam	1015
Grower/fattening	3166
Piglets	1654
Total	6000

Data Sourcing.

Data for the research was obtained through the following ways.

i. Information provided by the farm owners as well as their workers.
ii. Documents relating to hybrid power systems.

Configuration and System design.

Based on the following, the system components of the proposed system are determined.

❖ Integration of solar PV system.
❖ Waste quantification and characterization.
❖ Setup of anaerobic digestion-powered engine.

Design of Bio-Digester.

The fixed dome Anaerobic Digestion (AD) plant characterized by a hemisphere covering a cylinder at both the top and bottom is focused on. The fermentation chamber (V_f) and gas storage volume (V_{gs}) make up the total usable volume (V_{uD}) and is calculated as follows:

$$V_{\mu D} = V_{gs} + V_f = Q_{slurry} \times HRT(day) \qquad (3.1)$$

Where for this study, the hydraulic retention time per day (HRT) is taken as 55 days and Q_{slurry} is the total influent required (m^3/day). Feed stocks must be added into the bio-digester and water also usually added for optimal biogas production. [12] assertion that the ratio of manure added to the digester to water should be 1:1 was adopted in this work. Using the value of total organic matter (TOM), the total influent required (m^3/day) is determined as follows:

$$Q_{slurry} = \frac{TOM(kg/day)}{1} * 2 * \frac{1m^3}{1000kg} \qquad (3.2)$$

Biogas Electricity Production Potential from Waste Analysis.

The sum of the organic waste generated in the pig farm and the neighbouring households amounts to the feedstock to be treated (Q, kg day^{-1}) and is estimated as follows:

$$Q = \sum\left(N_{Hh} \times kg_{Hh} + N_{pf} \times kg_c\right) \quad (3.3)$$

As shown in table 3.2, kg_c is the daily weight in kilogram of waste produced per animal per development category while N_{Hh} is the number of households considered, and N_{Pf} is the number of animals per development category. The total waste production per day in a pig farm is about 5 kg/pig/day [12]. Waste produced per household per day is calculated as follows:

$$kg_{Hh} = MSW_p \times N_p \times (DM_{MSW} \times OF_{MSW}) \quad (3.4)$$

Where $\boldsymbol{MSW_p}$ is the municipal solid waste (MSW) generation per capita assumed to be 46% of the MSW and have a dry matter content ($\boldsymbol{DM_{MSW}}$) of 31%, $\boldsymbol{N_p}$ is the number of persons per household, while $\boldsymbol{OF_{MSW}}$is the organic fraction of MSW [13].

Table 2Developmental stage waste production per animal per day [14]

Development class	Dams	Piglets	fattening	Boars
Produced manure (kg/pig /day)	**3.0**	**0.35**	**2.3**	**3.6**

For biogas generation, the quantity of organic matter to be treated is determined by the percentage of volatile solids (%VS) within the solids and the percentage of total solids (% TS, wet basis). Computation of organic matter for AD treatment can be computed as follows:

$$TOM = VS_m \times Q \times TS_m \times (1 - loss_m) \qquad (3.5)$$

Siddiki, et al., (2021), had estimated the rate of biogas production ($\dot{V}_{biogas}$) in m^3 per day in the farm as follows:

$$\dot{V}_{biogas} = Y_m \times TOM = VS_m \times Q \times TS_m \times (1 - loss_m) \times Y_m \qquad (3.6)$$

Note that VS_m, TS_m, l_m and Y_m are the feedstock volatile solid content (in %), the feedstock

total solids content (in %), losses due to storage of and recovery of the biomass (%) and biogas yield of the volatile percentage (in Nm^3 /kg VS) respectively. Values of 80%, 20%, 90% and 0.36 has been taken for VS_m, TS_m, l_m and Y_m respectively.
From equation (3.6) daily production of methane on the farm can be estimated as follows:

$$V_{CH4} = x_{CH4} \times V_{bio} \quad (3.7)$$

Note that x_{CH_4} *is* proportion of methane in the biogas (x_{CH_4}, % $vol\, vol^{-1}$) and is taken as 65% [12].

From equation 3.7, the maximum electrical capacity of the biogas engine is determined as follows:

$$P_{el} = V_{CH4} \times 365 \times \frac{\eta_g \times LHV_{CH4} \times \eta_c}{AO_{hr}} [kW_e] \quad (3.8)$$

Where, η_g is the alternator efficiency (91.5%), LHV_{CH_4} is the lower heating value of methane (25.2 kWh/Nm^3[12]; η_c is the conversion efficiency (33.0%); and AO_{hr} the yearly operating hours (h/yr). The daily operating time of the motor-generator set is set at 21 hours (7,665 hours $year^{-1}$), which allows ample time interval for maintenance, as well as likely system shutdowns.

Solar PV Electricity Production Potential.

The proposed system adopted Huawei PV system with a rated capacity of 56 Kw, yielding an average output power of 8.82 kW per hour. The yearly power generation is calculated from equation (3.9).

$$P_{PV} = P_{hav} \times 24 \times 365 \quad (3.9)$$

Where P_{hav} is the hourly average power generation.

Pre-Feasibility, Design and Implementation of Hybrid System.

This optimized hybrid renewable power system that incorporates both solar energy and biogas from piggery waste was designed with Matlab and HOMER Pro. Figure 4shows the hybrid system study approach for the location.

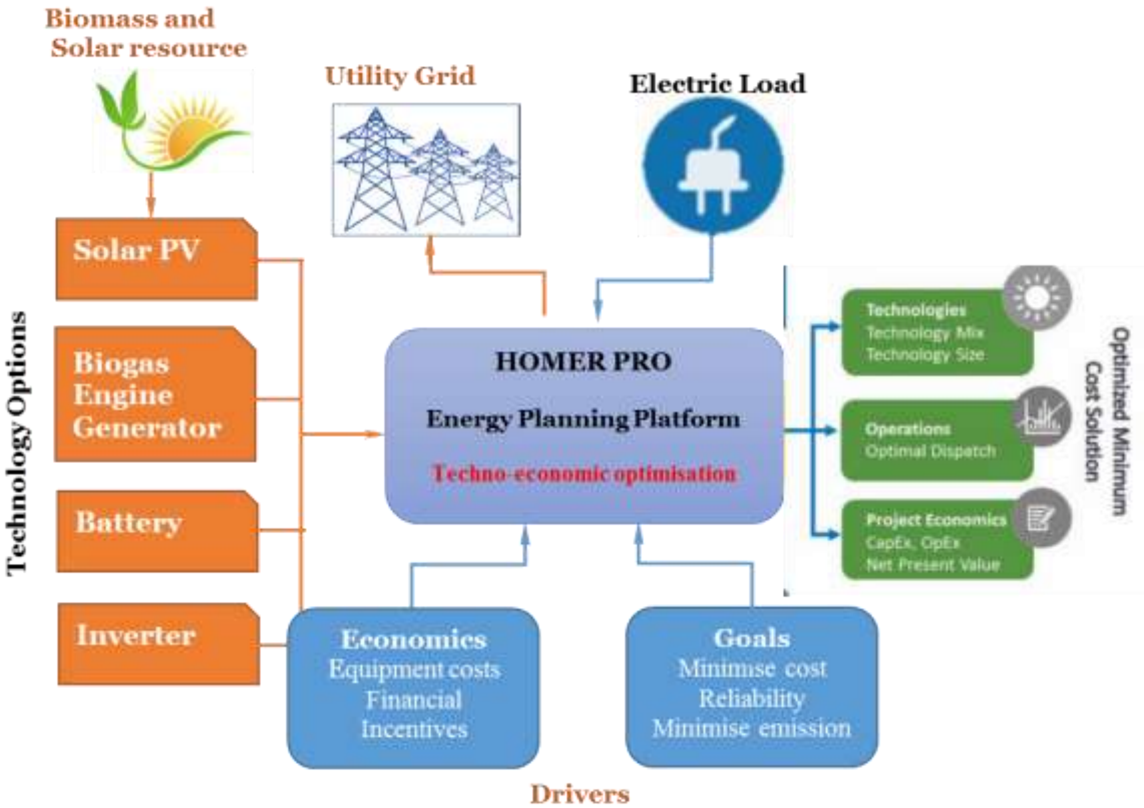

Figure 4:Key inputs and outputs modelling platform with HOMER Pro.

Estimation of Cost of Energy (COE)

The financial evaluation framework used in this study draws from guidelines for assessing investment projects in the energy sector [15]. The Economic evaluations were based on a range of factors including total investment cost (TIC), cost of electricity (COE), Operation and Maintenance cost (O&M), return on investment (ROI), payback time

(PBT), net present value (NPV), internal rate of return (IRR).

Total investment cost or Capital costs in dollars ($) is the sum of installation cost (C_{ins}) and the capital cost (C) of the components as follows:

$$TIC = C_{AD} + C_{EG} + C_{PV} + C_{inv} + C_B + C_{ins} \quad (3.10)$$

Where C denotes cost and subscripts AD, EG, PV, inv and ins denote Anaerobic Digester, electricity generator, solar PV, inverter, and installation.
The cost of the AD components is estimated using [16] model as follows:

$$C_{c,AD} = 18248 \times \xi^{0.8586}(1+e)^{(cy-py)} \times RC \quad (3.11)$$

Where ξ is the biogas or CH_4 volume in m^3/hour, e is the inflation rate (assumed as 2%) for conversion of equipment cost from currency year (CY), 2014 to present or analysis year (PY), 2023 and RC is exchange rate conversion factor from Euro to dollar which is 1.09 (I Euro=1.09 USD).

The cost of electricity (COE) generated by the system is calculated as follows:

$$COE = \frac{TAC}{AEO_{served}} \quad (3.14)$$

Where TAC and AEO denote total annualized cost of the system [$/yr] and annual energy output or total electrical load served [kWh/yr].
The annualized cost is calculated as follows:

$$TAC = CRF(r, N_{project}) \times NPC \quad (3.15)$$

Where r is the annual real discount rate [%] and N is the project lifetime in years
CRFis the capital recovery factor calculated as follows,

$$CRF(r, N_{project}) = \frac{r(1+r)^N}{(1+r)^N - 1} \quad (3.16)$$

Net present value (NPV) and Net present cost (NPC) were obtained using the following equations:

$$NPV = \sum_{n=0}^{N} \frac{\hat{C}_n}{(1+r)^n} = -TIC + \sum_{n=1}^{N} \frac{TAC}{(1+r)^n} \quad (3.17)$$

$$NPC = \sum_{n=1}^{N} \frac{TAC}{(1+r)^n} + TIC \quad (3.18)$$

Where $\hat{C}$ is the after-tax cash flow (Revenue –cost) which comprise capital outlays (CAPEX), operational outflow (OPEX), loan financing, incentives (if applicable) and taxes, TAC is the annual total costs ($), r is the interest rate, n is the analysis year and TIC is the total initial capital cost ($).

If inflation (e) is being considered, the TIC is adjusted to adjusted annual total cost (ATAC) to include inflation. ATAC is calculated using:

$$ATAC = TAC(1+e)^n \quad (3.19)$$

The cost of electricity generator (C_{EG}) is calculated as follows [16]:

$$C_{EG}(\$) = 15648 P_e^{0.536}(1+e)^{(cy-py)} \times RC \quad (3.12)$$

Where P_e is the rated electrical power of the biogas electric generator. The operation and maintenance (O&M) cost ($C_{O\&M}$) of the system can be estimated using the following formula [16]:

$$C_{O\&M} = 17.053 \times P_e^{0.478}(1+e)^{(cy-py)} \times RC \quad (3.13)$$

Table 3 shows the cost breakdown of the various components

Table 3Cost breakdown of the various components

Components	Unit Capital cost	O&M cost
PV	600 $/kW	360 $/yr
Inverter	300 $/kW	-
AD	1655 $/m^3	-
EG	1953 $/kW	-
AD+EG	4000 $/kW	4.$/op. hr

IRR can be determined by solving the following equation iteratively:

$$NPV = -TIC + \sum_{n=1}^{N} \frac{\hat{C}_n}{(1+IRR)^n} = 0 \quad (3.20)$$

In this study, a nominal (real) discount rate of 25% (8.7%) was chosen based on the commercial bank lending interest rate in Nigeria. Also, a 20 year of useful economic life and expected inflation rate of 15% was assumed.
The equation for PBT is as follows.

$$PBT = \frac{CAPEX}{\text{net annual cash flows}} \quad (3.21)$$

IV. RESULTS AND DISCUSSION.

Solar PV Capital cost and Power Output.

The economic assessment highlighted that the proposed hybrid system which required an initial capital cost of $674,128 attaining an advantageous Net Present Value (NPV) of $33,932 which is affirmed by the internal rate of return (IRR) of 17.9% and return on investment (ROI) of 16.2% as expected when compared to a grid supplemented with a diesel generator is economically viable even though it is not with grid electricity alone.

The proposed Huawei PV system was adopted with a rated capacity of 56 Kw, yielding an average output power of 8.82 kW per hour and a daily energy production of 212 kWh per day as shown in Table 4. The calculated annual energy generation from the solar PV installation reached 77,249 kWh, supported by an operational span of 4489 hours per year. Solar PV generation is limited to daylight hours, typically spanning from 06:00am to 18:00 p.m.

Table 4: PV performance.

Rated Capacity	56.0 Kw	Total Production	77,249 Kwh/yr
Capital Cost	$33,637	Maintenance Cost	673 US$/yr
Specific Yield	1,379 kWh/Kw	LCOE	0.0539 US$/kWh
PV Penetration	17.7 %	DC-AC Ratio	1.87

Economics Analysis of the Hybrid system.

The solar PV system implementation has the initial capital investment requirement amounting to US$33,637.41, making up to 5% ofthe hybrid system's initial cost and accompanied by an annual operation and maintenance cost of US$6,276.76. The standalone solar PV system exhibits a levelized cost of electricity of 0.0539 $/kWh. The initial capital cost of the hybrid system is $674,128.03 with the AD and biogas engine systems making up the highest share, over 94% of the total capital cost of system cost ($632,000) while the inverter contributed just 1% (US$8,490.63). The established cost of energy (COE) of this system stands at 0.246 $/kWh. The other cost parameters of the system are shown in Table 5.

Table 5: Capital cost of the hybrid system.

Components	Capital ($)	Replacement ($)	O&M ($)	Salvage Value ($)	Total ($)
BEG	632,000.00	0	59,264.33	-28,064.48	663,199.85
Grid	0	0	291,128.78	0	291,128.78
PV	33,637.41	0	6,276.76	-1,057.86	38,856.31
System Converter	8,490.63	2,430.84	0	-1,068.08	9,853.39
Hybrid system	**674,128.03**	**2,430.84**	**356,669.87**	**-30,190.43**	**1,003,038.32**

Table 6shows a summary of high positive Net Present Value of $33,932 indicating that the project the proposed project is indeed viable. The internal rate of return (IRR) of 17.9% was calculated, which is the rate of interest that generates the NPV. A high profitability or return on investment (ROI) of 16.2% is obtained. A simple payback period (PBT) of 5.43 years was calculated as the recovery period, which the expenses used for the project will be recovered.

Table 6: Economic analysis for the Hybrid system.

Economic indicators	Calculated values ($)
Total investment cost ($)	674,128.03
NPV ($)	33,932
Annual worth ($)	3,637
Cost of maintenance ($)	356,669.87
Profitability or ROI (%)	16.2 %
Payback period (years)	5.43 years
Internal rate of return (%)	17.9%

V. CONCLUSION AND RECOMENDATION

The estimated energy cost (COE) of this system which is 0.246 $/kWh is lower than the reviewed literature average of 0.30 $/kWh from diesel engine preferred alternative to the national gird by the Obeagu settlement. The net present value (NPV) and cost of electricity (COE) analysis suggested that the hybrid system, when compared to a grid electricity supplemented with a diesel generator shows profitability. The profitability or return on investment (ROI) is 16.2%, which is comparatively high compared to its cost shows the feasibility of this project and that it can be invested upon.

All these quantified macroeconomics variables indicated the potential in harnessing the piggery waste and solar power for improved electricity supply while enjoying the economic advantage over the use of both diesel-powered electricity as an alternative to the national grid supply. As a recommendation, the environmental impact of the proposed hybrid should form future researches as it should be compared with that of the national grid.

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