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Techno-Economic Optimisation of a Hybrid Solar-Hydro-Diesel-Battery Microgrid for Rural Electrification in Nigeria

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ABSTRACT: Consistent electricity supply is still a big problem in many rural areas of developing countries where the socio economic development is constrained by limited grid availability and poor infrastructure. This work summarised techno-economic analysis of hybrid microgrid system designed to improve access to electricity for a rural community in Ikot Ekpene Local Government Area of Akwa Ibom State, Nigeria. This system is based on solar photovoltaic (PV), micro hydro, diesel generation and battery energy storage system (BESS) to provide a steady and sustainable power supply. A comprehensive load analysis showed the peak demand to be about 7.5 MW, reflecting increasing residential and commercial activities within the community. The mathematical model of the hybrid system and the simulation were developed in MATLAB, and a genetic algorithm was used to determine the optimal sizes of the components and the operational schedule. The optimisation process aimed to enhance reliability, decrease operation cost and improve system performances. Results of simulation show the hybrid system can meet the demand of community load and work stably with the change of condition. The optimised system had a payback period of 0.65 years, an internal rate of return of 48 percent, and a positive net present value of ₦5,336,311, implying good financial viability. The combination of renewables and battery storage also significantly decreased reliance on diesel generation and bolstered the resilience of the system. The results of this study demonstrate the potential of hybrid renewable energy systems as a practical and sustainable solution for rural electrification in developing regions. The proposed framework provides valuable technical and economic insights for policy makers, energy planners and other stakeholders to scale up the generation of reliable electricity in remote areas.

KEYWORDS: Rural electrification, Techno-economic, Energy storage, Solar photovoltaic, Hybrid microgrid

1. INTRODUCTION

Electricity access is still the greatest driver for socio economic development, industrialisation and enhancement of quality of life. A consistent supply of electricity contributes to higher productivity, education and health care provision, and expanded business opportunities. While electrification has advanced on a global scale, many rural areas of developing nations are still experiencing extreme energy inadequacies [1, 2]. This problem is mostly experienced in sub Saharan Africa where the majority of people have no access to reliable electricity [3]. It is evident that energy consumption is very important driver for national economic growth especially for developing countries like Nigeria where insufficient electricity supply has been a major hindrance to productivity and industrial growth [4]. In the past, electricity generation has been concentrated in the urban and industrial areas and it has been found to be more lucrative to supply these areas with electricity than other areas because of the proximity of consumers and their high demand for electricity. National electrification plans typically prioritise cities while rural areas are neglected [5, 6]. Findings reported by [7] highlighted that two main constraints to extending infrastructure to rural areas are high capital investment costs and low expected revenue. As a result, many rural areas are still reliant on diesel generators or fragile grid expansions, leading to high costs of operation and environmental damage. Rural electrification can have a profound impact on economic resilience when enabled by decentralised energy systems as suggested by recent researches. According to [8], he indicated that rural areas have a huge potential of renewable energy, but these resources cannot be widely utilised. Hence, renewable energy based microgrids have been realised as a viable solution that can provide better reliability, lower transmission loss, and stronger energy security. However, dependence on one renewable resource is subject to intermittency and seasonal fluctuations, and tends to make the system unstable. [9] noticed that many microgrid applications do not become sustainable in the long run because of insufficient system optimisation, and poor integration of complementary energy sources. Hybrid microgrids that integrate the renewables, flexible alternating current transmission systems (FACTS), and the conventional power sources are more robust [10, 11]. Research such as [12] indicate that reliability is enhanced by the combination of solar, hydro and conventional backup generation to power continuously through changing environmental conditions. However many existing designs lack comprehensive optimisation framework and techno economic analysis, especially for large scale projects limiting practical implementation.

This study fills in these gaps by applying an optimal design of hybrid microgrid system consisting of solar PV, micro hydro, diesel generator (DG) and battery energy storage system (BESS) for a rural community in Ikot Ekpene Local Government Area of Akwa Ibom State, Nigeria. The proposed solution will address the rising pressure on electricity for residential and commercial uses, whilst maintaining the reliability of operation and economic feasability. A genetic algorithm is applied to optimise the system sizing and operation scheduling, and the feasibility and the long-term performance are assessed through the techno-economic analysis.

The issue of rural electrification is still a challenge to be tackled in many parts of the world especially in Sub Saharan Africa where electricity supply is still unreliable. Economic growth, social development and the provision of basic services, including healthcare and education, continue to be undermined by inadequate energy supplies. Recent research also shows that improving access to electricity is a key determinant in reducing poverty and in short term and rural long - term socio economic development. Decentralised energy systems have been repeatedly recognised as viable alternatives to more conventional grid extension. Microgrids, in particular, offer flexibility, scalability and suitability for remote areas with low population density. According to [13], microgrids reduce dependence on long transmission lines and improve energy access in the rural communities. However, their long term sustainability depends strongly on appropriate system planning, financial structures and demand characteristics. Enhanced control techniques have also been found to enhance the stability and performance of solar energy systems interfaced with electrical utilities. [14] showed that direct power control methods can substantially improve power quality and system stability in grid-connected wind energy systems, indicating the relevance and significance of intelligent control in future energy systems. Hybrid renewable energy systems have attracted attention because of their potential to integrate various energy sources and improve the reliability.

[15] emphasised that hybrid systems of renewable energy sources coupled with energy storage lead to more resilient and flexible systems than single source systems. Their results also showed the critical role of spatial and environmental influences on system outcome, especially in the application in the rural settings where resources are highly scattered. However, systems based on a single source of energy may face reliability issues due to intermittency and seasonal variations, even if they benefit from the merits of renewable technologies. [16] demonstrated that the reliability and cost effectiveness of hybrid renewable systems is greatly enhanced when compared with that of standalone systems. The study illustrated that the integration of renewables with storage and backup generation, increases system stability and decreases energy costs and environmental emissions. Recent studies have been increasingly devoted to developing optimisaion methods to enhance the performance of hybrid system. Multi objective and stochastic optimisation techniques to optimise the system flexibility and the operational efficiency, especially under uncertain demand and renewable generation, are discussed in [17]. They also concluded that implementing demand response strategies can enhance system reliability and lessen reliance on conventional backup means. [18] proved that an optimal size of PV based on a distribution system simulation tool greatly enhances the voltage stability and decreases the system loss, which concluded that proper sizing and accurate modelling and optimal design of renewable energy systems are very important.

Despite these advances, the studies are addressed separately for the technical performance and the economic feasibility. Numerous optimisation models are based on simplified assumptions, which do not adequately reflect load patterns, socio-economic context or operational constraints typically found in rural areas. This constraint diminishes the practical usefulness of such models, particularly in developing areas. In addition, too little emphasis has been placed on hybrid systems combining solar PV, micro hydro, diesel generation and battery storage within one integrated model. The joint operation of these parts in a real environment has also not been thoroughly investigated. Filling this gap is crucial for the formulation of reliable and scalable solutions for rural electrification.

This study addresses these limitations by designing an optimised hybrid energy system that combines solar photovoltaic, micro hydro, diesel generation and battery storage based on actual load demand and environmental factors. With technical modelling and techno-economic analysis, this study offers a realistic and scalable approach to rural electrification in developing countries.

2. MATERIALS AND METHOD

The materials used for this study were primarily instruments for data collection, and application tool for modelling, simulation and analysis. Load sizing and renewable resource availability were experienced-based acquisition of field data by site visit. The solar irradiance and hydro climatic characteristics of the site were analysed in detail for energy production feasibility. System parameters were modelled, simulated and calculated using MATLAB. These tools allow to derive mathematical models of the energy source, perform optimisation routines and visualise the system behaviour with respect to different operating conditions. The methodology was designed so that a systematic and accurate evaluation of the proposed hybrid microgrid could be realised. The study was inspired by the incessant problem of inadequate electricity supply in rural area, most especially in Nigeria where grid reliability is deemed low and suffers credibility crisis. The selected case study location in Ikot Ekpene Local Government Area was chosen based of the availability a running river which is suitable for a micro hydro generation and high solar irradiation is available for any season especially in dry season. These natural resources are also ideal for the use of renewable energy technologies. The research protocol was carried sequentially starting with decoupling of meteorological and load data. Subsequently mathematical models for each energy source are derived, and the system is simulated using MATLAB and optimised using a genetic algorithm. The final stage involved techno economic analysis to evaluate system feasibility and performance.

2.1 Load Assessment and Data Acquisition

Load estimation was conducted through physical inspection and interaction with residents within the selected community as shown in Table 1.

Table 1: Network data

Residential Load		**Commercial load**	
Units (amount)	**Load (kW/hr) per unit**	**Units (amount)**	**Load (kW/hr) per unit**
High load consumption building (900)	4.70 (4.23 MW)	Churches (19)	2.567 (0.049 MW)
		Health center (1)	0.320
Low load consumption house (400)	2.90 (1.16 MW)	Lock up shops (55)	2.22 (0.1221 MW)
		Wielding stations(3)	33.5(1.8425 MW)
Total	**5.39 MW**	**Total**	**2.0136 MW**

Residential, commercial and institutional electricity demands were evaluated to establish realistic load profiles. The overall load was estimated to be 7.4 MW for both existing and future load. The findings showed that the national grid electricity was available for only 1.5 hours on the daily average, which corroborated the necessity of owning a dependable and sustainable energy system. The predicted load was then used as a reference to calculate the capacity of each energy source in the hybrid configuration. All modelling and optimisation calculations were then made on the basis of this load profile.

2.2 System Architecture

The proposed microgrid consists of solar PV modules, a micro hydro power plant, a diesel generator, battery energy storage and a power conditioning unit as shown in Figure 1. The system was designed to operate in both grid connected and standalone modes depending on availability of the national grid.

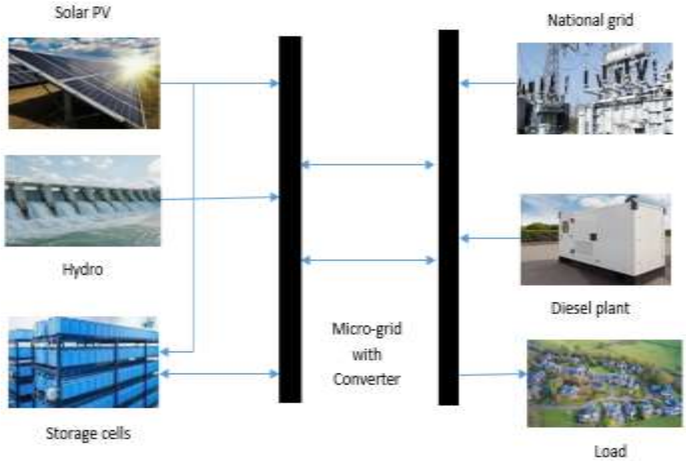

Figure 1: Microgrid design of the hybrid network

The electric power produced by solar PV system and micro hydro generator is at first in the form of direct current. This power is converted into AC with the help of power electronic converters before supplying to the load. When there is surplus energy produced in off-peak times, it is stored in the battery system. The diesel generator is used as a backup to guarantee availability during extended periods of low renewable energy production. With this arrangement, power flow can be controlled flexibly, and stable operation is realised even when load and environment conditions change.

2.3 Solar Photovoltaic System Modelling

The solar PV subsystem was designed to supply a significant portion of the community load. The expected design for the solar PV system is shown in Figure 2.

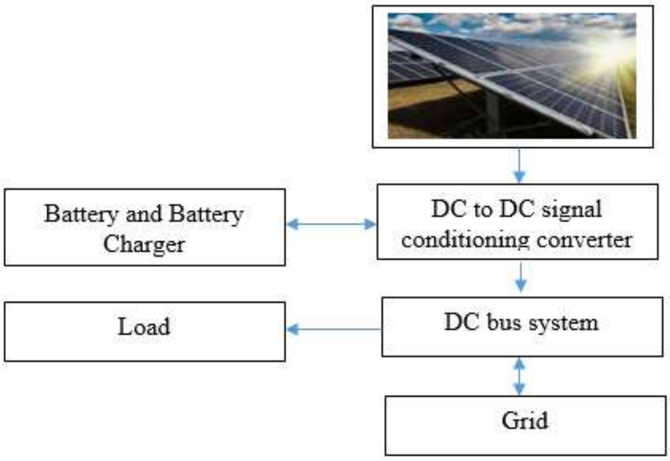

Figure 2: Solar PV design for the microgrid

The PV array sizing was calculated from the load demand, solar irradiance and system efficiency. A tolerance margin was added to compensate for variations in the solar availability and system losses. The quantity of panels was calculated using the rated power of a panel, the peak sun hours, and conversion efficiency [19 – 21]. The PV system was interfaced with a DC bus, a battery storage system, and a power conditioning unit for efficient energy transfer and stable voltage.

Since;

$$P_{Load} = P_{PV} \quad 1$$

Where P_{Load} and P_{PV} represents the load demand and the power output from the PV.

Then it implies that the number of panels required at 570 W per rating and the inverter was dependent on the load demand of the existing load of the location with 20% tolerance hence;

$$P_{PV} = PP_W \times S_P \times E_{fp} \times 20\% \quad 2$$

Where PP_w represents the solar panel wattage (which was 570 KW), S_P represents the peak sunshine hours and E_{fp} represents the efficiency of the panel (the ability of the power to convert sunlight to electricity which was 72%).

Hence, the number of panels N_p needed for the design was shown in Equation 3.

$$N_p = \frac{P_{PV} \times 20\%}{PP_W \times E_{fp}} \quad 3$$

Hence the number of panels required was determined to be;

$$N_p = \frac{5.39 \times 10^6 \times 0.2}{570 \times 10^3 \times 0.75} = \frac{1078000}{4275} = 252\ panels \quad 4$$

The 252 panels was obtained to generate an equal amount of power with 20% tolerance that would march with the load demand. However, the actual panel would be obtained based on the optimisation outcome.

2.4 Micro Hydro System Modelling

The micro hydro sub-system was designed according to the hydraulic properties of the accessible water source. The important parameters under consideration were hydraulic head, flow rate, and turbine efficiency. These values were then applied in determining the potential power output from the micro hydro plant. The size of the water reservoir and the flow channel were calculated to provide enough water for continuous operation. The turbine size was chosen to fit the predicted power output while ensuring a steady power output under different flow conditions. The micro hydro system has a considerable impact on base load support because of its rather stable output profile.

The major design components of the hydro-plant was the determination of the power output of the hydro plants P_{HP}, the optimal operation time T_o and the required velocity of the river V and the hydraulic head H_h because [22];

$$P_{HP} = (H_H \times V) \log(T_o) \quad 5$$

The output and the operational time remains the actual parameters to be deployed for the operational time. The schematic image of the micro-hydro system is shown in Figure 3.

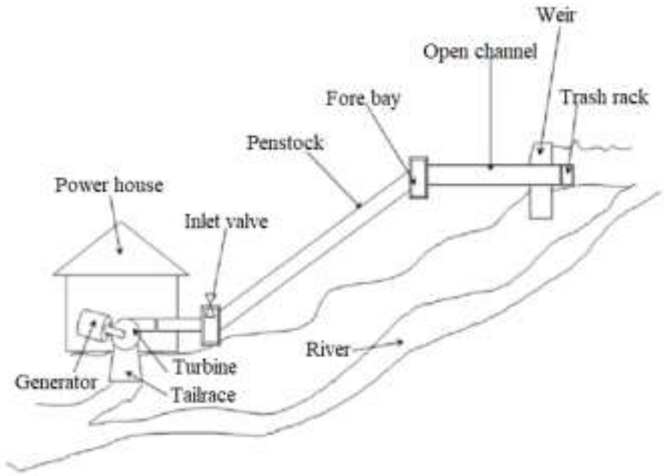

Figure 3: Schematic diagram of the micro- hydro plant [23]

From Figure 3, it was imperative to determine the hydraulic high and the water velocity of the dam that would satisfy the optimal hydro-system for a satisfactory micro-grid design.

The model for H_H is shown in Equation 6.

$$H_H = \frac{9.81 \times logV^2}{P_{HP}} \quad 6$$

Hence, the volume of the dam V_D system for the water storage is shown in Equation 7.

$$V_D = (P_{HP} \times 10^\wedge 6)/(H_H) \quad 7$$

The length L_D, the width W_D and the height H_D of the dam are shown in the following Equations 8 to 10;

$$H_D = \frac{V_D \times 1.2}{3 \times V} \quad 8$$

$$L_D = \frac{V_D}{H_D} \times 0.00312 H_H \quad 9$$

$$W_D = \frac{V_D}{L_D \times H_D} 1.032 \quad 10$$

The turbine power rating P_{tub} is shown in Equation 11.

$$P_{tub} = 1.2017 H_H \quad 11$$

Irrespective of the outcome of the optimisation, the sizing of the hydro-turbine would not be changed. Hence, the time t_d it would take to fill the mini-dam is shown in Equation 12.

$$t_d = \frac{V_D \times H_D \times P_{tub}}{2.89g} \quad 12$$

Where g represents the gravitational force (9.81m/s^2).

2.5 Battery Energy Storage Modelling

The battery energy storage system was designed to compensate power fluctuations and improve supply availability. Battery capacity was calculated considering the required autonomy time, load demand, and processing of renewable sources. This enables excess energy produced during periods of low demand to be stored and then dispatched during peak demand or periods of weak renewable energy generation. The size of battery was calculated by using the basic electrical formulas related to the voltage and current ratings. The storage system is a key element to ensure the continuity of supply and the robustness of the overall system [24].

The power output of the battery P_{bat} is shown in Equation 13.

$$P_{bat} = P_{Load} \times 0.2 \quad 13$$

Form the battery, the power was equal to the load demand with a tolerance of 20% and to determine the actual power, the power output from the solar PV and the hydro would be utilised in increasing the power of the battery [25, 26] is presented in Equation 14.

$$P_{bat} = 20\% \times P_{PV} + 30\% \times P_{HP} + P_{NG} \quad 14$$

Where P_{NG} represents the power from the national grid.

The number of batteries N_{bat} required is shown in Equation 15.

$$N_{bat} = \frac{P_{bat}}{I_{batt} \times V_{batt}} \quad 15$$

Where I_{bat} and V_{bat} represents the current and the voltage rating of the battery.

2.6 Diesel Generator Modelling

A diesel generator was used as backup power source to maintain the continuous power supply. The size was chosen to cover the load in times of low renewable energy supply or high utilisation. When needed, the generator also helps to charge the battery bank. The performance of the diesel generator was adapted to be more realistic in fuel consumption and power output. This guaranteed correct modelling in simulation and in optimisation.

The model for the power output of the diesel plant P_{diesel} is shown in Equation 16.

$$P_{diesel} = 1.2 \times P_{load} \quad 16$$

The number of diesel generators N_{diesel} necessary for the micro-grid is shown in Equation 17.

$$N_{diesel} = \frac{P_{diesel}}{P_{rating}} \times 1.065 \quad 17$$

Where P_{rating} represents power rating of the diesel generator.

2.7 Optimisation Strategy

A genetic algorithm was used to optimise the size and the operation schedule of the microgrid components. The objective function was designed to minimise the system cost while meeting the load demand along with the operational constraints. The decision variables were the power outputs of each energy source and the length of time they were active. The constraints were derived from technical constraints, energy availability, and system reliability requirements. The optimisation procedure systematically modified the parameters of the system to result in an optimal configuration that balanced performance, cost and reliability.

From the data obtained, the model for each of the power outputs from the energy sources would be obtained with the outcome utilised to form the objective function whose schematic model is shown in Equation 18.

$$obj\ fun \begin{pmatrix} expected\ grid\ power\ and\ time\ of\ operation \\ for\ each\ power\ source \end{pmatrix} = a_0 + \sum Power\ output\ from\ each\ energy\ source + estimated\ timing\ of\ each\ power\ sources \quad 18$$

Where a0 represents the coefficient that would be determined using least square method. The initial guesses for the optimal micro-grid power is shown in Table 2.

Table 2: Output power coefficient initial guess for the optimization

Parameters	Coefficient values
National grid	1
Solar panels power	1
Solar battery power output	1/2
Micro hydro power output	1/2
Diesel plant	2

The value (1) means that the national grid would generate power equal to the total load, ½ implies that solar battery would generate half of the total load and so on. The outcome of the optimisation would adjust the guesses to the expected optimised outcome.

The constraints to the optimisation is based on the operational time of each device and the operating cost which would have a relationship between the power output and the operation time as shown in Equation 19.

$$Operating\ cost\ (each\ energy\ source) = (system\ installation\ cost)^D + (power\ output \times operating\ time)^x \quad 19$$

Where D and x where factors utilised based on the type of energy source device modelled.

2.8 Techno Economic Evaluation

The techno economic studies were performed to determine whether the suggested microgrid would be financially viable or not. The cost components taken into account were the equipment cost, the installation cost, the management cost and the operation and maintenance cost. Economic metrics including net present value, internal rate of return and payback period were considered for optimised system configuration. The outcomes resulting from this study will shed light on the ability to maintain the proposed system over a long period of time as well as the economic feasibility in case of supplying electricity to rural area.

The equipment cost model utilised is presented in Equation 20.

$$equipment\ cost = cost\ of\ the\ solar\ PV\ system\ components + cost\ of\ the\ micro-hydro\ compoents + cost\ of\ utilizing\ national\ grid + transportation\ cost \quad 20$$

The transportation cost is 10% of the addition of cost of solar PV components and cost of micro-grid components. The management cost is 30% of the equipment cost, installation cost is 5% of the equipment cost while operations and maintenance cost 20% of the equipment cost.

3. RESULTS AND DISCUSSION

3.1 Load Estimation

The estimated load profile for the case study community is shown in Figure 4. The overall load demand was seen to fluctuate from 7.1 MW to 7.5 MW with the upper bound as the peak demand scenario. This difference is due to the adjustment of some consumption among residential and commercial users, especially when business is conducted under increased energy consumption.

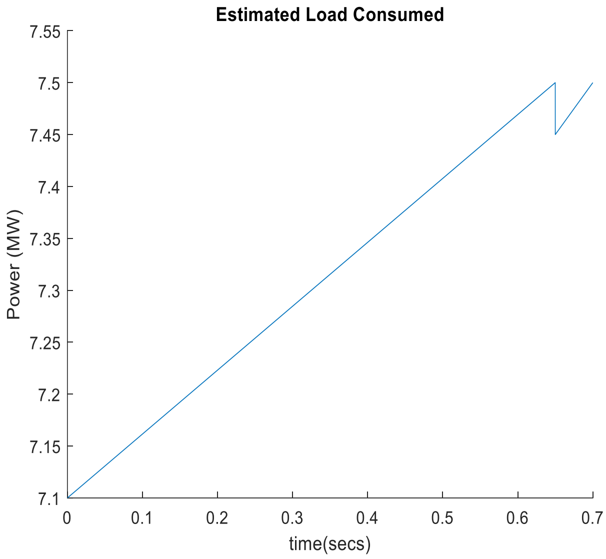

Figure 4: Estimated load consumption

The 7.5 MW estimated load includes a tolerance margin to accommodate for future growth on the load side and fluctuations in consumption during the day. This load magnitude was used as reference in the design and optimisation process of the hybrid microgrid system.

3.2 Power Output from the National Grid

The electrical characteristics of the national grid supply were analysed to determine its contribution to the microgrid. The current waveform obtained from the simulation is shown in Figure 5, while the corresponding voltage profile is illustrated in Figure 6. The current magnitude was approximately 60 A, while the voltage level was observed to be about 0.25 kV.

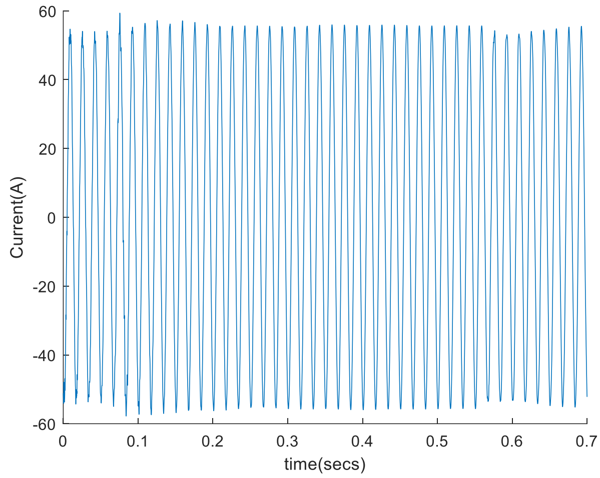

Figure 5: Current signal from the national grid

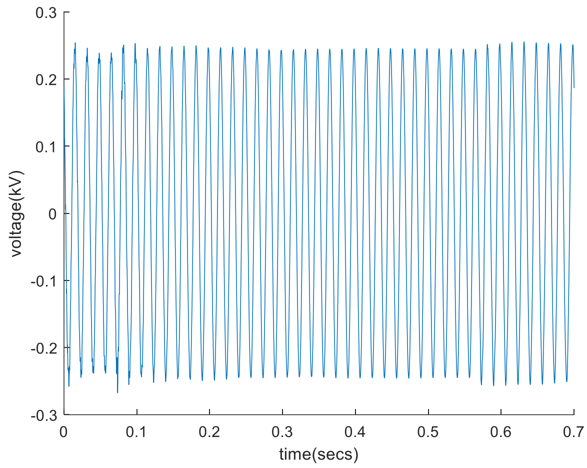

Figure 6: Voltage signal from the national grid

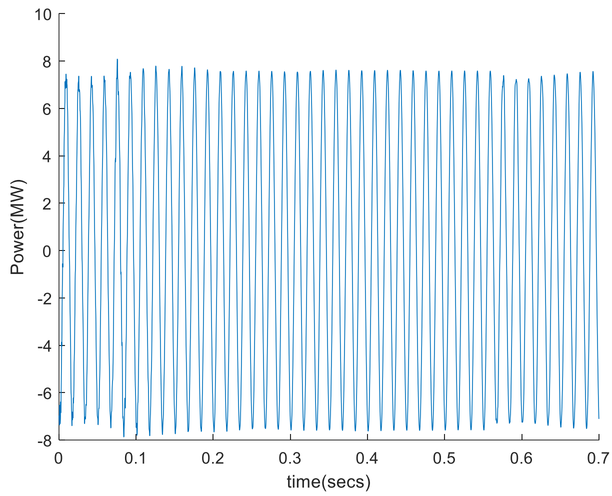

Figure 7: Power output from the national grid

The resulting power output from the national grid, shown in Figure 7, indicates that the grid was capable of supplying sufficient power to meet the estimated load demand during its operational period. However, due to the limited availability of grid supply, reliance on this source alone would not guarantee continuous electricity access. This further justifies the integration of additional energy sources within the microgrid.

3.3 Solar Photovoltaic System Performance

The performance of the solar photovoltaic system was analysed through its current, voltage and power output profiles. The current signal from the PV system, as shown in Figure 8, was approximately 47 A, while the voltage level shown in Figure 9 was around 0.242 kV. The resulting power output, presented in Figure 10, was approximately 7.31 MW.

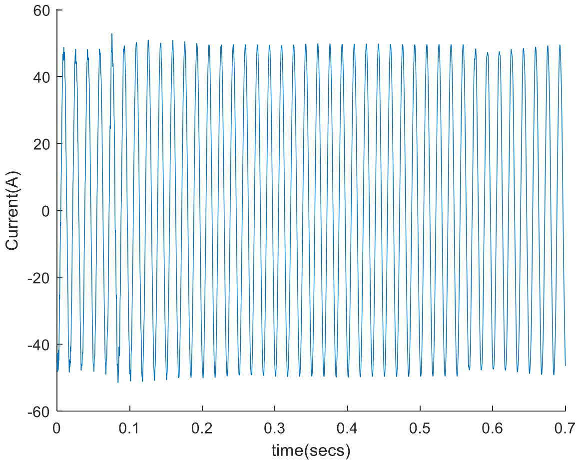

Figure 8: Current signal from the solar PV

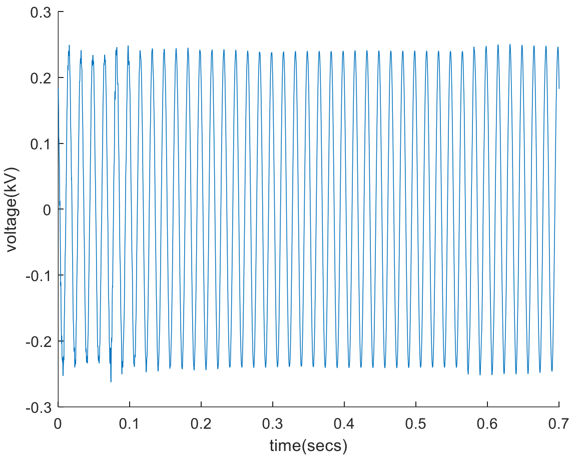

Figure 9: Voltage signal from the solar PV

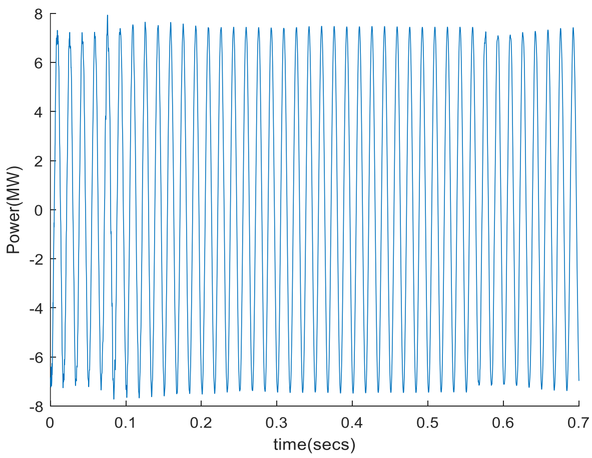

Figure 10: Power output from the solar PV

This output closely matched the estimated load demand, indicating that the solar PV system was appropriately sized. The result confirms the suitability of solar energy as a primary power source within the proposed microgrid, particularly during periods of high solar irradiance.

3.4 Diesel Generator Performance

The diesel generator served as a supplementary power source to enhance system reliability. The current waveform of the diesel generator, shown in Figure 11, recorded a value of approximately 43 A, while the corresponding voltage level in Figure 12 was about 0.262 kV. The resulting power output, presented in Figure 13, was approximately 7.36 MW.

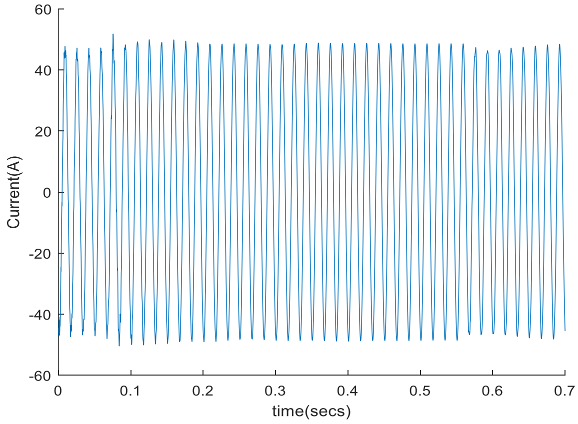

Figure 11: Current signal from the Diesel generator

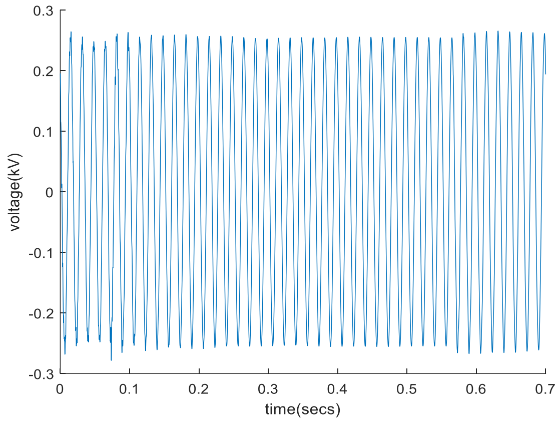

Figure 12: Voltage signal from the Diesel generator

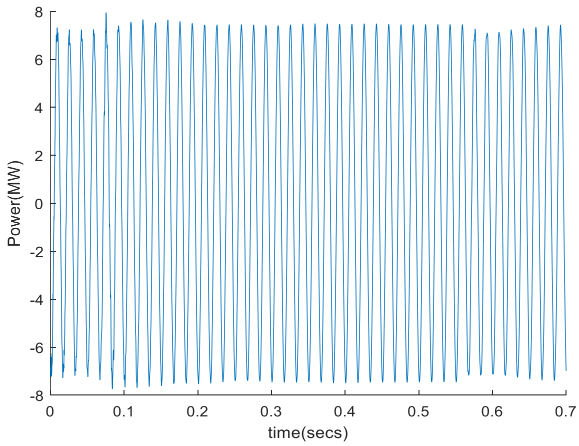

Figure 13: Power output from the diesel generator

This output exceeded the estimated load demand slightly, indicating that the diesel generator was capable of supporting both the load and auxiliary functions such as battery charging when required. The results demonstrate that the diesel generator provides a reliable backup during periods of low renewable energy availability.

3.5 Micro Hydro System Performance

The performance of the micro hydro system is illustrated in Figures 14 to 16. The current output was approximately 45 A, while the voltage level was around 0.255 kV. The corresponding power output reached approximately 7.44 MW.

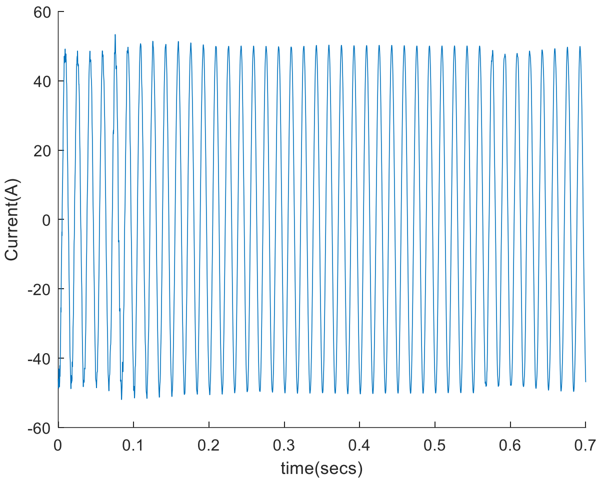

Figure 14: Current signal from the micro-hydro generator

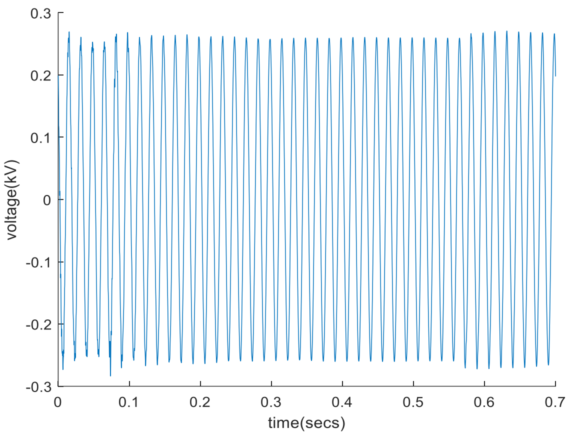

Figure 15: Voltage signal from the micro-hydro generator

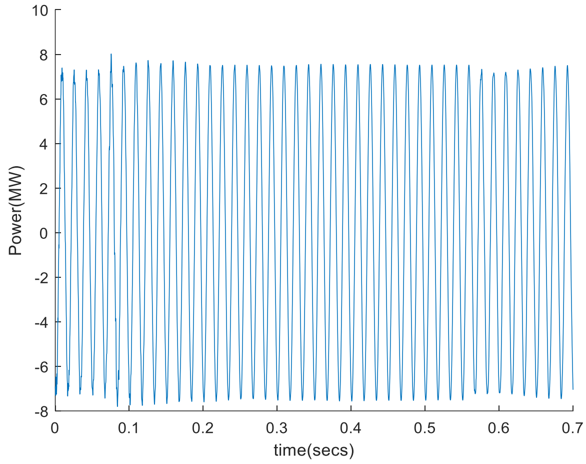

Figure 16: Power output from the micro-hydro generator

These results indicate that the micro hydro system was able to deliver a stable and reliable power supply. The relatively consistent output makes the hydro component a strong contributor to base load support within the hybrid microgrid.

3.6 Battery Energy Storage Performance

The battery energy storage system played a critical role in stabilising power supply and managing energy fluctuations. The current output from the battery system, shown in Figure 17, was approximately 47.4 A, while the voltage level presented in Figure 18 was about 0.227 kV. The resulting power output, illustrated in Figure 19, reached approximately 7.61 MW.

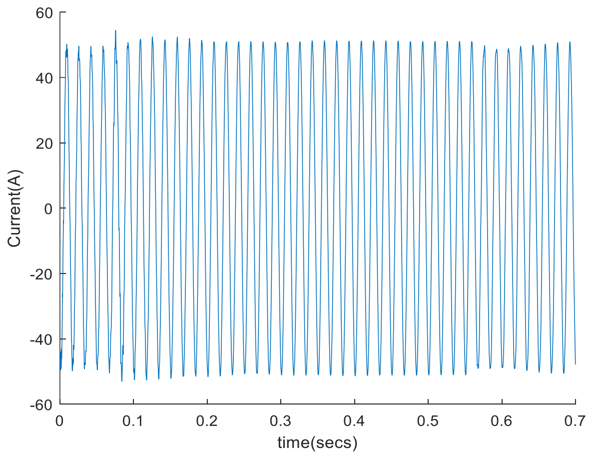

Figure 17: Current signal from the battery

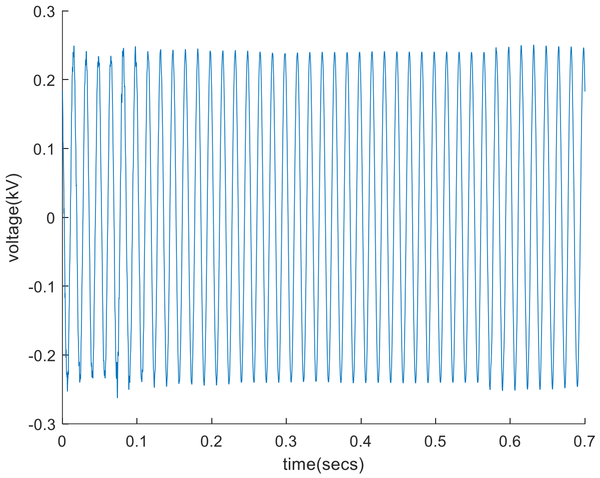

Figure 18: Voltage signal from the battery

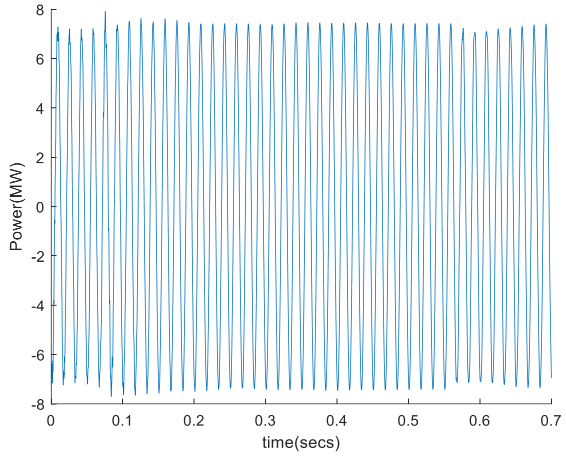

Figure 19: Power output from the battery

These results demonstrate that the battery system effectively supported the load during periods of reduced generation from renewable sources. The battery also enhanced system reliability by smoothing power variations and ensuring continuous supply.

3.7 Optimisation Results

The optimisation results revealed notable improvements in system performance. The optimal power sizing of the microgrid components is presented in Table 3. Compared to the initial configuration, the diesel generator capacity was reduced from two units to 1.5 units, while the battery capacity was increased from 0.5 to 1. This adjustment allowed for extended battery operation during nighttime and reduced dependence on diesel generation.

Table 3: Power sizing of the energy source elements of the micro grid

Source elements	Initial guess (before optimisation)	After optimisation
National grid	1	1
Solar PV	1	1
Battery	1/2	1
Micro-hydro	1/2	1/2
Diesel	2	1.5

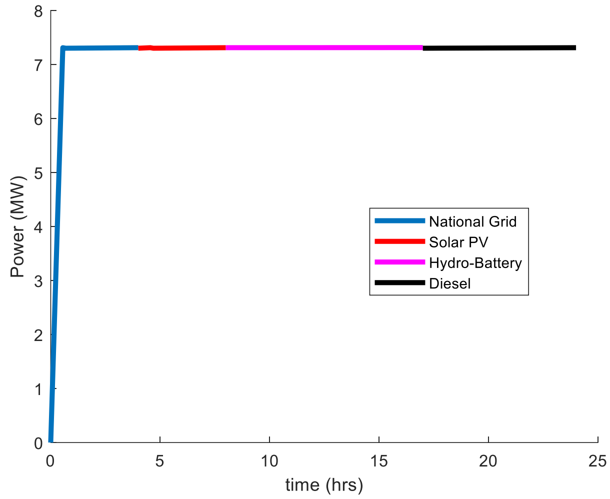

Figure 20: Optimal operational time of the source elements of the micro-grid

The optimal operational timing of the energy sources is illustrated in Figure 20. The results show coordinated operation among the various sources, ensuring that energy demand is met efficiently throughout the day.

3.8 Techno Economic Analysis

The techno economic evaluation of the optimised microgrid system is shown in Table 4. The analysis indicates a payback period of approximately 0.65 years, an internal rate of return of 48 percent and a positive net present value of ₦5,336,311.

Table 4: Techno economic analysis of the micro-grid

Economic parameters	Values
PP	0.65 years
IRR	48%
NPV	₦5,336,311

These results indicates strong economic viability, despite the relatively high initial investment associated with integrating multiple energy sources. The short payback period reflects the system's ability to generate consistent energy output while reducing reliance on costly diesel fuel. Furthermore, the long term operational benefits and extended system lifespan contribute to overall cost effectiveness.

The results confirm that the proposed hybrid microgrid provides a reliable, sustainable and economically feasible solution for rural electrification. The integration of renewable energy sources with storage and backup generation enhances energy security and supports long term socio economic development within the community.

4. CONCLUSION

The study reported herein included detailed techno-economic evaluation of a hybrid microgrid system consisting of solar

PV, micro hydro, diesel generation and battery energy storage for the purpose of rural electrification in Ikot Ekpene Local Government Area of Akwa Ibom State, Nigeria. The motivation for this study was the long-standing problems of erratic grid supply and limited availability of power in rural towns. With the aid of extensive modelling, simulation and optimisation, the study demonstrated that a well designed hybrid energy system can deliver reliable, sustainable and cost effective electricity supply to underserved areas. The load analysis indicated a community peak demand around 7.5 MW, a sign of increasing residential and commercial energy consumption in the area. It can be observed from the simulation result that the energy sources contributed effectively to the overall system performance, with the micro hydro and solar PV systems deliver a stable and clean power, the diesel generator guarantees the system reliability in the low renewables resources period. The battery energy storage system contributed significantly in balancing supply and demand, which further improved system stability and operational flexibility. The optimisation led to a substantial performance improvement by means of the modification of the power contributions of the individual components. The results showed that reducing the dependence on diesel generation while increasing battery capacity enhanced operational efficiency and reliability. The techno economic analysis also confirmed the feasibility of the proposed system with a payback period of 0.65 years, IRR of 48% and positive NPV. These results indicate that hybrid renewable energy systems are capable of providing both technical and economic feasibility if properly designed. In overall, the findings confirm that integrating renewable energy sources with conventional backup systems and energy storage provides a practical solution for rural electrification in developing regions. The developed microgrid model offers a scalable and adaptable framework that can be replicated in similar communities across Nigeria and other developing countries facing energy access challenges. Further study is to be carried out in order to consider advanced energy management strategies including predictive control and real time optimisation that would improve the system efficiency. Also, the application of smart monitoring systems and demand side management techniques may enhance even further the responsiveness of the system and lessen the running costs. Furthermore, upcoming studies may investigate the integration of new energising technologies such as hydrogen storage and electric vehicle integration, to enhance system sustainability. These would lead to more in depth insight in to the indirect benefits of hybrid microgrid deployment.

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