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Exploring Rural Electrification Possibilities in Southern Nigeria

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Abstract: In many rural areas of developing countries like Nigeria, the national electricity grid is still out of reach. For these communities, a hybrid power generation approach that mixes locally sourced renewable resources like solar energy with diesel generators is seen as a smart and eco-friendly solution. However, there's a lack of detailed techno-economic studies on PV– diesel hybrid systems for off-grid electrification in Nigeria. This study aims to pinpoint the best system configurations for remote communities in Nigeria. To do this, we focused on three off-grid rural communities Azungwu, Agidiase, and Agidiehe situated in Ogwashi-Uku, Delta State, as our case studies. We looked at various system setups, including standalone options (solar-only, and diesel-only) as well as hybrid combinations. By utilizing meteorological data, community load profiles, diesel fuel prices, and component costs, we employed the HOMER software tool to find the most suitable system sizes across different scenarios, all while aiming to minimize the net present cost (NPC). We also evaluated the chosen configurations using other economic indicators like initial investment cost, total annual operating cost, and cost of energy (COE), along with generation shares and CO_2 emission levels.

The results we've gathered show that, across all the agencies we looked into, the hybrid solar–diesel system stands out as the most reliable option. For this scenario, the best configuration yields a net present cost (NPC) of NGN 2,668,052. (cost of energy: 0.563 NGN/kWh) for Azungwu, NGN 2,739,955 (cost of energy: 0.443 NGN/kWh) for Agidiase, and NGN 214,156 (cost of energy: 0.737 NGN/kWh) for Agidiehe. Additionally, when we apply these optimal setups, we find that Azungwu and Agidiase achieve a renewable energy fraction of 88% of their total generation, while Agidiehe reaches an impressive 95%. In terms of CO_2 emissions, the optimal system for Azungwu produces only 6% of what a diesel-only unit would emit, with Agidiase at 16% and Agidiehe at 13%. The configurations detailed in this paper can serve as a valuable guide for designing cost-effective renewable electrification systems for these communities and other villages with similar needs and environmental conditions.

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I. INTRODUCTION

Access to electricity is a top priority for governments, especially in countries where it is crucial for fundamental tasks like lighting, refrigeration, and operating household appliances. (Ajuzie U.C et al. 2020).

In many rural areas of developing countries like Nigeria, the connection to the national power grid is still quite limited. This is largely due to challenging landscapes and low population densities, which make extending the grid a tough financial challenge. As a result, harnessing energy from local renewable sources such as wind and solar has emerged as a viable and eco-friendly solution (Mamaghani et al. 2016). Moreover, the increasing global prices of fossil fuels and the rising concerns about greenhouse gas emissions have made these renewable options even more appealing (Najafi et al. 2015), remarkable attention has been directed toward green renewable technologies for catering growing energy demand (Abd-Essalam et al., 2023).

Renewable energy sources (RES) are abundant in most parts of the world, and, unlike fossil fuels, can be harnessed without any cost for the resource. In this regard, many governments have already started to finance renewable technologies by means of direct grants, loans and tax incentives (Liu et al. 2012). Electricity generation in Nigeria through hydro, solar, geothermal, biomass or other RES is subjected to an annual maximum 20% depreciation regime for income tax purposes (Fobio et al, 2020).

Despite the inherent advantages of renewable energy sources (RES), several technical challenges must be addressed to ensure system reliability and self-sufficiency. The primary obstacle is the intermittent nature of renewables, where atmospheric variability leads to substantial seasonal and daily circle fluctuations in power output (Bekele & Boneya, 2019). To mitigate this instability, previous research has advocated for the integration of energy storage systems, such as batteries (Hafez et al., 2022), or the hybridization of RES with dispatchable non-renewable technologies like

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diesel, natural gas, or biomass generators (Montuori et al., 2024). These hybrid systems, comprising at least two energy sources, aim to achieve superior electrical efficiency and a more consistent power supply.

While RES installations often involve higher initial capital expenditures compared to conventional diesel units, they offer significant long-term benefits, including reduced operational costs through lower fuel consumption (Kalantar & Mousavi, 2020) and a smaller carbon footprint (Bentouba & Bourouis, 2016). Furthermore, scaling these systems can lead to a notable reduction in the Cost of Energy (COE) and Net Present Cost (NPC) as they meet larger electrical loads (Diab et al., 2016). Given the complexity of variables involved—such as resource availability, load profiles, and fluctuating fuel prices—computational optimization is essential (Gu et al., 2017). Techniques such as Genetic Algorithms, Cuckoo Search, and Game Theory are frequently employed to optimize component sizing and minimize total lifecycle costs (Ekaba et al., 2025; Yousefi et al., 2017). Case studies, such as those by Arceo et al. (2018) in Australia and Flores et al. (2016) in Jordan, emphasize that while optimal configurations can reduce diesel consumption by over 21% and lower environmental impacts, they require a delicate balance between upfront investment and long-term sustainability. To navigate these trade-offs, the Hybrid Optimization Model for Electric Renewables (HOMER) has become a foundational tool for performing techno-economic feasibility studies and sensitivity analyses on hybrid microgrids (Singh & Baredar, 2016).

The "fuel-saving" potential of these systems is not merely an environmental benefit but a strategic necessity in the face of erratic fuel supply chains and extreme price inflation. By utilizing optimization software like HOMER, researchers can model "what-if" scenarios that account for future spikes in diesel costs, thereby "future-proofing" the energy investment against market volatility. Finally, the role of intelligent energy management systems (EMS) is becoming increasingly central, as they allow for real-time load shedding and priority-based power distribution, which maximizes the utility of stored battery energy. This holistic approach transforms a simple power setup into a smart microgrid capable of supporting both residential needs and small-scale industrial growth in underserved communities.

(Dekker et al. 2022). Using HOMER, Alsharif (2017) pinpointed the ideal configuration of PV and battery systems, demonstrating that it offers a smart and cost-effective way to power diverse cellular networks. In another analysis using HOMER, Brandoni and Bošnjakovic (2017) discovered that a well-designed hybrid system, which combines PV arrays, wind turbines, and internal combustion engines, could satisfy around 33–55% of the energy demands for a wastewater treatment facility in Sub-Saharan Africa, all while keeping energy costs below the local grid prices. Likewise, Marneni et al. (2025) utilized HOMER to find the optimal sizing for a solar PV system aimed at enhancing the voltage profile of a rural feeder with a peak load of 3.06 MW in Mysuru, India.

It is widely recognized that meeting electrical demand through hybrid systems utilizing a combination of renewable energy sources (RES) and non-renewable backups is more practical than relying solely on a single RES. This preference arises because single-source systems often lack the reliability to meet fluctuating loads without excessive oversizing, which drastically inflates the initial capital expenditure (CAPEX). By integrating dispatchable sources like diesel generators or battery energy storage systems (BESS), the intermittency of solar and wind can be "smoothed," ensuring a constant power supply even during peak demand or periods of low resource availability.

Research in this field frequently focuses on optimizing these configurations to minimize the Cost of Energy (COE) and the Net Present Cost (NPC). For instance, studies in Honduras have successfully optimized hybrid wind, PV, and biomass systems for rural electrification, proving that diversifying the renewable mix reduces the need for large-scale storage. Similarly, Dekker (2022) demonstrated that the optimal integration of wind and diesel generation in remote Jordanian settlements achieved a 21.3% reduction in annual fuel consumption. This highlights a critical benefit of hybridization: the "fuel-saving" mode, where renewables take the primary load and the generator only operates during deficits, thereby extending the mechanical lifespan of the engine.

The Hybrid Optimization Model for Electric Renewables (HOMER) software has become the industry standard for conducting these techno-economic feasibility studies, sensitivity analyses, and microgrid optimizations (Singh & Baredar, 2016; Dekker et al., 2022). The software's ability to simulate thousands of configurations allows researchers to find the "least-cost" solution while maintaining a specific Loss of Load Probability (LLP).

Utilizing this software, Alsharif (2017) identified that a PV-battery configuration offers a highly energy-efficient and cost-effective solution for powering heterogeneous cellular networks, where uptime is critical. Furthermore, Brandoni and Bošnjakovic (2017) applied HOMER to a wastewater facility in Sub-Saharan Africa, finding that a hybrid mix of PV, wind, and internal combustion engines could meet 33–55% of the energy demand at a lower COE than local grid rates. Additionally, Marneni et al. (2025) employed the software to determine the ideal sizing for solar PV generation to improve the voltage profile of a 3.06 MW peak load rural feeder in Peru. These global cases underscore a shifting paradigm: hybrid systems are no longer just "green" alternatives; they are strategically superior for grid stability and long-term economic sustainability in regions with high fuel costs and unreliable central grids.

It is widely established that hybrid energy systems—integrating both renewable energy sources (RES) and conventional power—offer superior reliability compared to standalone renewable installations. Relying exclusively on a single RES often necessitates significant system oversizing to compensate for diurnal and seasonal fluctuations. Consequently, extensive research has focused on the

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feasibility of various configurations, including PV–wind (Arribas et al., 2023) and wind-fuel cell systems (Khan and Iqbal, 2025). For instance, Shaahid and Elhadidy (2022) demonstrated the techno-economic viability of PV–diesel–battery setups, while Dang et al. (2024) highlighted that regional climates dictate optimal configurations, noting that wind dominates in Ireland while PV diesel systems become more cost-effective for loads exceeding 13 kWh/day.

From a practical standpoint, Bekele and Palm (2010) identified the PV –wind-diesel-battery hybrid as the most viable solution for remote Ethiopian communities. Environmental assessments further support these systems; research by Hafez and Bhattacharya (2012) quantified microgrid emissions, while Ajlan et al. (2017) found that PV–utility–diesel configurations could reduce CO_2 emissions by 70% and lower the Cost of Energy (COE) by 45% compared to diesel-only generation. Similarly, Hossain et al. (2017) observed that hybridizing diesel units in Malaysia significantly reduced carbon intensity and energy costs.

System connectivity also plays a role, as Aaslid et al. (2022) noted that grid-tied hybrids often achieve lower COEs than off-grid systems by exporting surplus electricity. Furthermore, sensitivity analyses by Dorji et al. (2022) indicate that a 20% reduction in PV costs can lower the Net Present Cost (NPC) by up to 8%. Despite the vast renewable potential in Delta State, Nigeria, there remains a critical shortage of feasibility studies regarding these technologies. Specifically, there is a lack of comprehensive techno-economic research focused on hybrid configurations, such as PV–diesel systems, for the city of Asaba. This current research is focused on discovering the best mix of available RES to meet the energy needs of three rural communities in Ogwashi-uku. These regions have been selected according to the National Bureau of statistic (NBS, 2020). NBS (2020) provides statistical data such as population, access to power network, and distance from large urban areas. Meteorological data of solar irradiation (NIMET 2017). Solar irradiation, wind speed, and electricity demand of each location are provided as inputs to HOMER software to conduct the techno-economic analysis. We're looking at three different scenarios: single component systems like diesel and solar, as well as a hybrid option that combines both solar and diesel. Each of these scenarios is modeled using HOMER software, and we focus on the Net Present Cost (NPC) as the key economic indicator to figure out the best sizing for each setup. After determining the optimal configuration, we assess it against a range of economic and environmental factors, such as initial capital costs, operating expenses, cost of energy (COE), reliability factors (RF), and emissions of pollutants. While HOMER does have its limitations, it's widely recognized in the literature as a valuable tool for achieving the goals of this study. The need to optimize hybrid systems has become even more pressing due to the wild fluctuations in fuel prices in the Nigerian energy market. With Premium Motor Spirit (PMS) skyrocketing to ₦1100 and diesel hitting ₦1200/L in 2025, many remote and commercial operations are finding traditional diesel-only generation no longer viable. Unlike the stable fuel price assumptions seen in past studies, the current situation in Nigeria calls for a "Renewable-First" approach, where diesel shifts from being the main power source to a backup option for emergencies. The soaring fuel costs significantly reduce the payback period for investments in solar panels and batteries, making the Net Present Cost (NPC) of hybrid systems far more appealing compared to fossil-fuel alternatives.

II. DESCRIPTION OF THE CONSIDERED AREAS

- *Location and Population*

Delta State has one of the lowest electrification rates in Nigeria (NBS, 2020). There are many ways of generating energy in homes. However, due to the comparatively low cost of installation and little maintenance required, the micro-sources used in this work are diesel generators and solar PV.

For this study, three locations with drastically low power coverage, Azungwu, Agidiase and Agidiehe all located in Ogwashu-uku, have been selected. Based on the master plan of rural electrification with REA of Nigerian (REA Nigeria 2020), three small cities were chosen from previously mentioned Ogwashi-uku city. The regions with lack of access to electricity grid and the chosen communities within these regions are critically analyze. Ogwashi-uku which house these rural communities is a mid-size place in Delta state, Nigeria with a population of approximately 50,137 people. Agidiase which is situated in the northern part of Ogwashi-uku with a tropical climate which is characterized by mild and sunny days. Azungwu is located in heart of Ogwashi-uku has high elevation which results in harsh climate conditions compared to the other selected communities.

- *Load Estimation*

The community energy needs were calculated using a base load of 141 W, which accounts for lighting, radio receivers, and a 30 W reserve. Because the local economy is centered on daytime business and farming, energy consumption peaks during the day. Critical infrastructure included in the model consists of a PMS station (1.4 kW) and a school (1.3 kW), the latter of which operates from 8:00 a.m. to 2:00 p.m. with lighting and office equipment. Additionally, 400 W was allocated for public lighting per region. Following the load distribution approach by Ekoko et al. (2018), Figure 1 presents the hourly load profiles for both weekdays and weekends. To keep things concise, we're only looking at the load profile for this specific location. You'll notice that electricity usage dips during the early morning and late evening hours. This happens because offices close and people head home between 8 PM and 7 AM.

The determined overall load profile of each location is then provided to HOMER. Next, in order to add randomness to the load data to make it more realistic, timestep- to-time-step and day-to-day variability values of 20% and 15% are applied to the provided raw data.

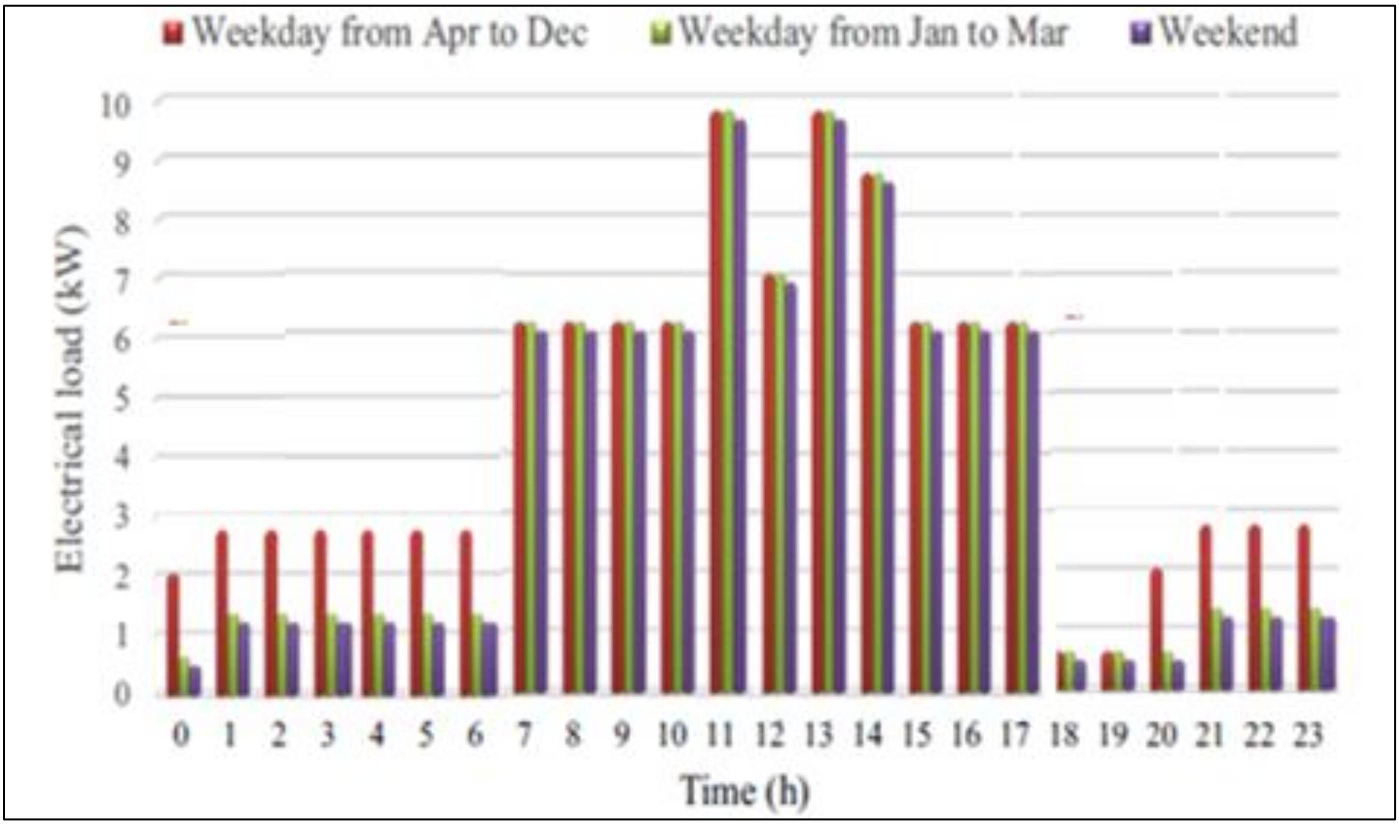

Fig 1 Daily Electrical Load Profile During Weekdays for Azungwu

The peak load in the generated profile for Azungwu, Agidiase, and Agidiehe is determined to be 18.9 kW, 15.1 kW and 9.8 kW. Figure 2 depicts the average load, based on the generated load profiles, for each months of the year for the considered region. The determined average yearly load for Azungwu, Agidiase, and Agidiehe is 4.3 kW, 3.6 kW, and 2.6 kW.

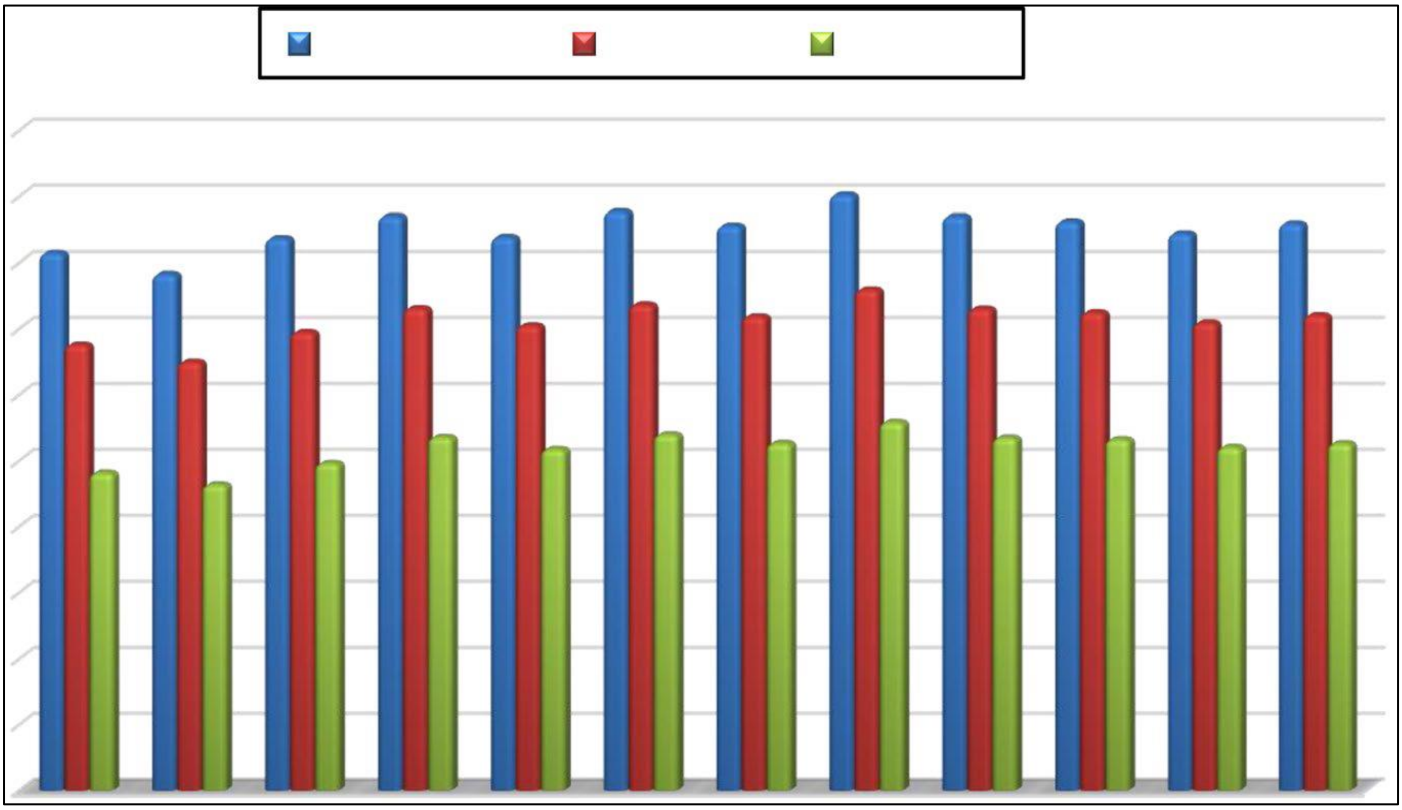

Fig 2 Availability of Energy Resources

➢ *Solar Irradiation*

Utilizing the climatic information from NASA surface meteorology and solar energy (NASA 2017), the average monthly solar irradiations are determined for each location (Figure. 3). Among selected locations, Azungwu has the highest average yearly irradiation (3.145 kWh/m^2) and Agidiehe has the lowest one (2.326 kWh/m^2). As can be noticed in Figure. 3, during Rainy season (months of May–August), solar irradiation reaches its lowest values, leading to small power production from the PV source.

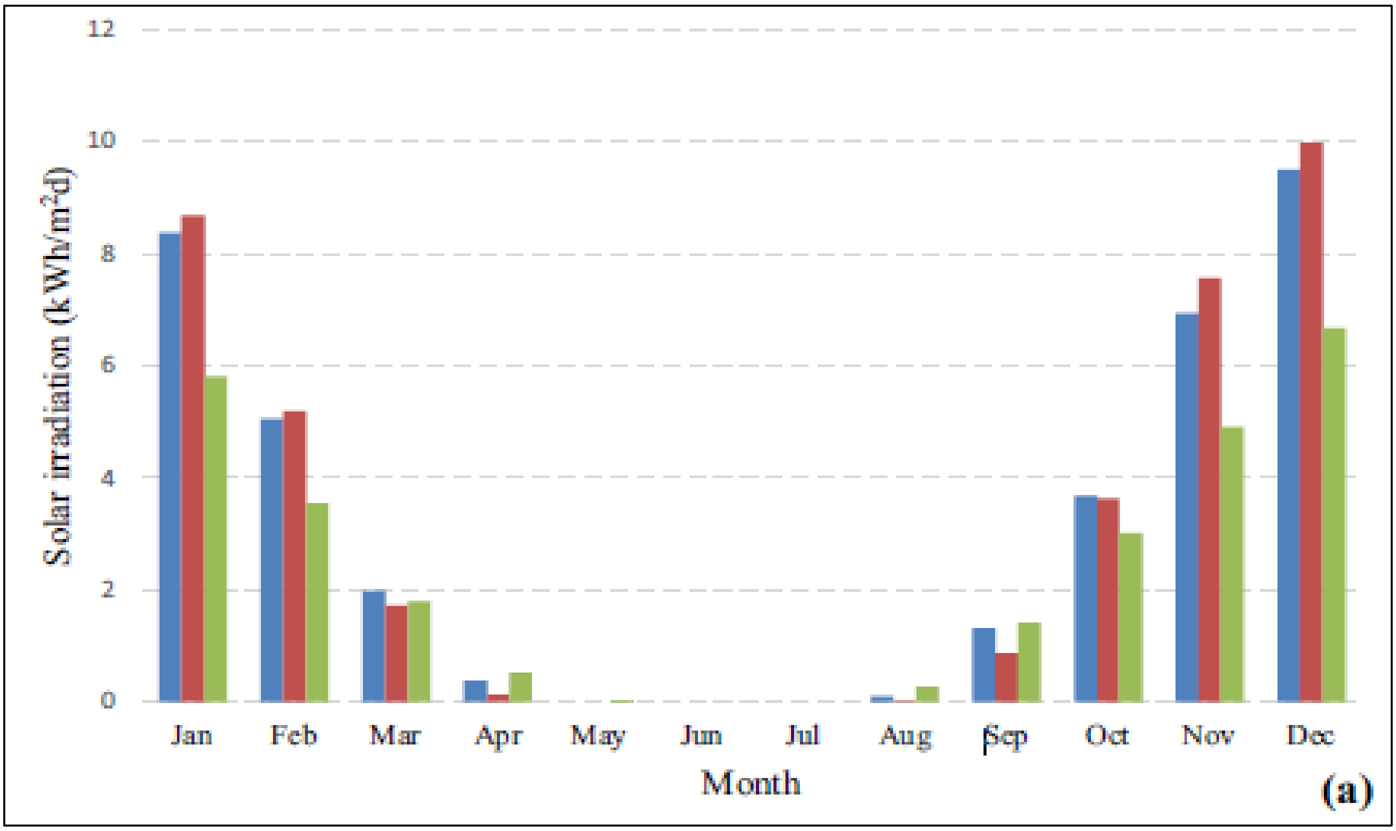

Fig 3 Monthly Solar Irradiation

➢ *Diesel Fuel*

In recent years, Nigeria has seen a significant spike in fuel costs; PMS rose from ₦200 in 2023 to ₦1100 in 2025. Consequently, diesel price estimates for remote areas have doubled during this period, increasing from ₦600/L to ₦1200/L.

III. CONSIDERED CONFIGURATIONS

➢ *Major Components*

The major components of hybrid systems are photovoltaic panels, diesel generators, batteries, and power converters.

➢ *Diesel Generator*

Power systems that rely entirely on renewable energy technologies often raise concerns about their reliability, mainly because these energy sources can be intermittent (Ekaba et al., 2025). To find a middle ground between ensuring a dependable energy supply and meeting sustainability targets, integrating diesel generator systems with renewable energy setups can be a viable solution. In this study, we examined Generac diesel generators with power ratings of 15 kW, 20 kW, 30 kW, and 48 kW, all of which are anticipated to have an operational lifespan of around 30,000 hours i.e approximately 25 years, provided they receive regular maintenance and periodic (HOMER Energy, 2017; Generac, 2017). The replacement cost is estimated to be 100% of the initial capital cost because the entire unit is replaced at the end of its life, while the annual operation and maintenance expenses are assumed to be 10% of that capital cost (Mamaghani et al., 2016). To avoid the problem of wet stacking, which is a condition in diesel engines where unburnt fuel passes into the exhaust system, creating a thick, dark, tar-like substance. This occurs when an engine operates at a low load (typically less than 30–50% of its capacity) or runs for extended periods without reaching its optimal operating temperature (cK power.com). That's why it's crucial to maintain a proper load level to ensure effective combustion and reliable engine performance. In this study, we made sure the diesel generator operated above a certain minimum load ratio. Specifically, we set the minimum loading level at 37% of the generator's rated capacity. This approach aligns with the guidelines from HOMER Energy Pro (2022).

➢ *Photovoltaic Array*

A Photovoltaic (PV) array is a complete power-generating unit composed of multiple solar modules linked in series or parallel to meet specific voltage and current requirements. These modules contain interconnected solar cells that convert sunlight directly into DC electricity via the photovoltaic effect. By scaling the number of panels, an array

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can range from small residential setups to massive utility-scale solar farms. You can determine the power output of a solar panel by using the formula in Eq. (1) (Fabio et al 2020).

$$P_{PV} = f_{PV}\, Y_{PV} \frac{I_t}{I_s} \tag{1}$$

Where f_{PV} represents the PV derating factor, Y_{PV} represent the rated capacity of the PV array (kW), I_t is This represents the global solar irradiance incident on the PV array surface (measured in kW/m²), relative to the standard test condition (STC) irradiance used to define the system's rated capacity and I_S is the standard irradiance used for rating PV modules, which is 1 kW/m² under standard test conditions. To account for real-world performance losses including soiling, shading, aging, and temperature effects, a derating factor of 0.9 is utilized. This value aligns with the standard defaults suggested by HOMER Pro (HOMER Energy, 2017) to bridge the gap between theoretical nameplate capacity and actual energy yield. The analysis utilizes two cost-effective polycrystalline PV modules from JinkoSolar, with pricing sourced directly from the manufacturer (Jinkosolar, 2017). One such module is the JinkoSolar JKM200PP-60 cell**,** which features a 200 W rated capacity and an efficiency of 14.8%. This module has a surface area of 1.637 m² (dimensions: 1650 × 989 × 40 mm) and operates at a rated maximum power voltage (Vmp) of 30.3V, rated maximum power current (Imp) is 7.99A, Open-circuit voltage (Voc) is 37.35A, and short-circuit current (Isc) 8.65 A and Efficiency of 14.8% under standard test conditions (STC). The 300W module (JinkoSolar JKM300PP-72 cell) instead has a surface area of 1.634 m^2 with dimensions of (1954X992X40mm), maximum power voltage (Vmp) of 36.1V, rated maximum power current (Imp) is 8.31A, Open-circuit voltage (Voc) is 45.1A, and short-circuit current (Isc) 8.55 A and Efficiency of 15.48% under standard test conditions (STC). According to manufacturer specifications, the PV arrays are assigned a functional lifespan of 25 years. The replacement cost is estimated at 90% of the initial capital expenditure, while annual operation and maintenance (O&M) costs are projected at 1% of the primary investment. (Nusrat et al, 2020).

➢ *Battery*

Batteries store electricity in a chemical form, allowing this energy to be recharged and reused later. Since power production from renewable sources can change quickly due to weather conditions, battery storage has become a key player in ensuring a steady and reliable power supply. It also helps minimize the number of start/stop cycles for backup diesel generators in hybrid systems (Nfah & Ngundam, 2023). For this analysis, we've chosen two lead-acid battery models from Surrette and Hoppecke as comparable options in HOMER. The prices for each battery type were taken from the manufacturers' websites (Hoppecke-Batterien-GmbH 2017; Surrette-Ltd 2017), which indicate that the expected lifetimes for Surrette and Hoppecke batteries are 17 and 20 years, respectively. We assume that the replacement cost will be about 90% of the initial capital cost, and the annual operation and maintenance expenses are estimated to be 10% of the capital cost.

➢ *Power Converter*

The inverter is a key component of a PV system, responsible for converting DC power from the PV module and energy storage system into AC power for load supply. When surplus AC power is available from the utility, the rectifier converts it into DC for battery storage. In this study, SMS Sunmate converters rated at 4.2 kW, 5 kW, 8 kW, and 10 kW are considered, with cost data obtained from the manufacturer (SMS Sunmate Technologies Inc., 2024). The replacement cost is assumed to be 87% of the initial capital cost (Mamaghani et al., 2016), while annual operation and maintenance costs are estimated at 10% of the initial capital cost. The converter and rectifier efficiencies are taken as 98% and 85%, respectively (Nusrat et al, 2020).

➢ *Scenarios*

To conduct a thorough and systematic assessment for each chosen location—exploring all viable combinations of renewable energy sources (RES) and diesel generator integration, we define and evaluate three distinct case scenarios. These scenarios are considered to showcase various hybrid system configurations and operational strategies, enabling a comprehensive comparison of technical performance, economic feasibility, and sustainability potential. Among the cases analyzed, we pinpoint the most suitable and cost-effective configuration for microgrid planning and long-term deployment, based on a detailed set of evaluation criteria. We utilized the HOMER Pro software (HOMER Energy Pro) to perform an in-depth techno-economic optimization for each proposed scenario and community. Through simulation and sensitivity analysis, HOMER identifies the optimal component sizing, dispatch strategy, and lifecycle cost for every configuration. As shown in Figure 4, the system configurations explored within HOMER can be summarized as follows:

- Diesel generator (Case 1)
- Solar (Case 2)
- Solar–diesel hybrid (Case 3)

IV. MATERIALS AND METHODS

When we look at the weather data and the energy needs of the communities, along with the price of diesel fuel and the cost of various components, we can figure out the best (most cost-effective) way to size the system for different scenarios. During this optimization process, the Net Present Cost (NPC) is treated as the main economic indicator. The configurations we come up with are then compared using other advanced economic indicators, as well as environmental metrics and generation fractions. In this section, we present the indicators used in this study, which include NPC, Cost of Energy (COE), initial capital costs, total annual operating costs, and the generation fractions.

➢ *Net Present Cost (NPC)*

NPC, or Net Present Cost, reflects the total expenses of a system throughout its entire lifespan. This includes various costs such as capital, replacement, operation and maintenance (O&M), fuel, salvage, and any penalties related to emissions. You can calculate NPC using Eq. (2):

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$$NPC(NGN) = \frac{TAC}{FRC} \quad (2)$$

Where TAC is the total annualized cost, FRC is the factor of returning capital given by Eq. (3):

$$FRC(NGN) = \frac{i(1+i)^N}{(1+i)N-1} \quad (3)$$

Where N is the project's lifespan (in years) and i is the yearly interest rate. Replacement cost is considered to factor in the economic effect of using components that don't last as long as the project.

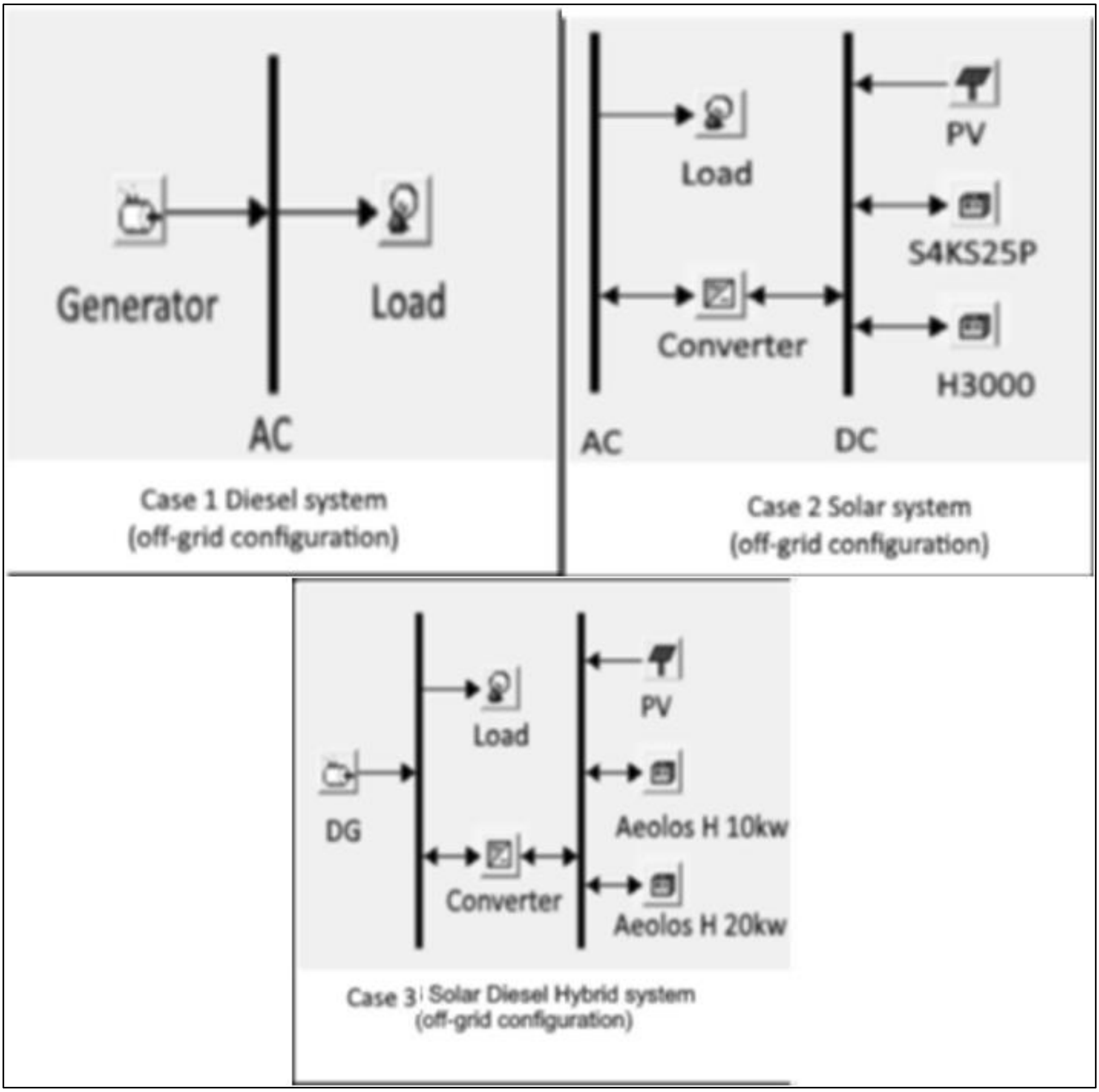

Fig 4 Homer Simulation of the Three Scenerio

➢ *Levelized Cost of Energy (COE)*

COE is the average cost per kilowatt hour (/kWh) of useful electrical energy produced by the system which is calculated using Eq. (4).

$$COE = \frac{C_{TANN}}{E_{Is}} \quad (4)$$

Where E_{ls} is the electrical energy supplied to microgrid and C_{TANN} is total annualized cost of the entire system (NGN/year).

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- *Initial Capital Cost*

The initial capital cost is essentially the total amount you need to invest upfront to buy and set up all the system components before you can start using them. This cost covers everything from purchasing to installing the equipment during the project's commissioning phase. If you're looking at a hybrid system that includes batteries, solar panels, a diesel generator, and a converter, you can figure out the overall initial capital cost by using Eq. (5), which adds up the individual costs of each component.

$$\text{Initial capital cost} = N_b C_b + \frac{P_{st}}{P_{sb}} Cs + P_{gt} C_{gref} + \frac{P_c}{P_{cb}} C_c \quad (5)$$

Where N_b represents the number of batteries in the system, and C_b is the cost of the energy storage system per individual battery. P_{st} denotes the total power generated by all solar modules (in kW), while P_{sb} is the rated power output of a single solar panel (in kW), and Cs is the cost of the solar energy system per panel. P_{gt} is the total power output of the diesel generator (in kW), C_{gref} is the cost per kilowatt of generator capacity. Pc is the power of the converter, Pcb is the power of base converter and Cc is cost of the base converter.

- *Total Annual Operating Expense (TOC)*

The operating costs represent the total annual expenses incurred to ensure the proper functioning and maintenance of all system components over a one-year period. These costs typically include fuel consumption (if applicable), routine maintenance, repair and replacement services, operational labor, and any other recurring expenditures required to keep the system running reliably and efficiently. The total operating cost reflects the combined contribution of each component's individual operating expense within the system. It provides an overall measure of the yearly financial requirement needed to sustain system performance. The total annual operating cost can therefore be determined using Eq. (6):

$$TOC = \sum_{i=1}^{n} C_{om,i} + c_f + \sum_{i=1}^{n} C_{R,i} - \sum_{i=1}^{n} C_{s,i} \quad (6)$$

Where n is the number of components of the system, $C_{OM,I}$ is the annual operation and maintenance (O&M) cost for i^{th} component of the system, C_f is annual total fuel cost, $C_{R,i}$ is annualized replacement cost for i^{th} component of the system and C_S,i is the salvage value of component i. In HOMER, the economic evaluation assumes that all system components depreciate in a linear manner over their useful lifetime. This means that the value of a component decreases at a constant rate from the time it is installed until the end of its specified lifetime. Consequently, the salvage value of a component at the end of the project period is calculated based on the fraction of its remaining useful life. In other words, if a component has not fully exhausted its operational lifetime by the end of the analysis period, its residual (salvage) value is assumed to be directly proportional to the unused portion of its life.

- *Shares of Electricity Production*

F_{ren} as specified in Eq. (7), is the ratio of the electrical production originating from renewable power sources to the total electrical production:

$$f_{ren} = \frac{E_{ren}}{E_{tot}} \quad (7)$$

In our analysis, E_{ren} refers to the electricity coming from renewable sources (kWh), and E_{tot} is the total electricity produced by the system (kWh). Using the approach suggested by Fabio et al (2020), we can figure out how much each energy source is actually contributing. This makes it easier to see which technology is doing most of the work at any given time. For example, the solar contribution is captured by the photovoltaic fraction, E_{pv} or F_{pv}.

As shown in Equations 8 and 9, F_{pv} is simply the energy produced by the solar panels (E_{pv}**)** divided by the total energy (E_{tot}). Basically, this tells us what portion of the overall electricity comes from solar. Looking at these fractions helps us understand the system's renewable share and how well each source is performing throughout the year.

$$f_{pv} = \frac{E_{PV}}{E_{tot}} \quad (8)$$

$$f_{dg} = \frac{E_{dg}}{E_{tot}} \quad (9)$$

Where E_{pv} E_{dg} is the energy produced by photovoltaic and the diesel generator.

V. RESULTS AND ANALYSIS

The optimal system configurations for Cases 1–3 across all sub-grids are summarized in Tables 1, 2, and 3. To facilitate a rigorous economic comparison, four key performance indicators were evaluated: initial capital cost (NGN), annual operating cost (NGN/year), Net Present Cost (NPC in NGN), and Levelized Cost of Energy (COE in NGN/kWh). These metrics provide a comprehensive financial profile, enabling the identification of the most cost-effective solution for each site ((Fabio et al, 2020). Furthermore, the analysis accounts for environmental sustainability through annual CO_2 emission calculations and technical performance via total yearly electricity generation from solar PV and diesel components.

- *Optimized Designs for Azungwu*

Table 1 Optimal Results for the Proposed Setup in Azungwu

S/N		Case 1 (diesel)	Case 2(Solar)	Case 3(solar/diesel)
	PV (KW)	-	130	160
	Generator (KW)	20	-	20
	Converter (KW)	-	10	10
	F_{PV} (%)	0	100	88

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	F_{dg} (%)	100	0	12
	PV (KW/year)		142549	102493
	DG (KW/year)	58780	-	13744
	CO_2 emissions (Kg/year)	74391	-	14699
	Annual operation of DG(h)	6237		1136

Table 2 Optimal Results for the Proposed Configuration in Agidiase

S/N		Case 1 (diesel)	Case 2(Solar)	Case 3(solar/diesel)
	PV (KW)	-	120	18
	Generator (KW)	20	-	10
	Converter (KW)	-	10	10
	F_{PV} (%)	0	100	87
	F_{dg} (%)	0	0	13
	PV (KW/year)		143357	68095
	DG (KW/year)	55011	-	10545
	CO_2 emissions (Kg/year)	70263	-	11916
	Annual operation of DG(h)	8759		1060

Table 3 Optimal Results for the Proposed Configuration in Agidiehe

S/N		Case 1 (diesel)	Case 2(Solar)	Case 3(solar/diesel)
	PV (KW)	-	140	90
	Generator (KW)	10	-	10
	Converter (KW)	-	10	10
	F_{PV} (%)	0	100	95
	F_{dg} (%)	100	0	5
	PV (KW/year)		109455	48555
	DG (KW/year)	30434	-	2146
	CO_2 emissions (Kg/year)	38333	-	4980
	Annual operation of DG(h)	8759		423

The optimization results and the associated costs for the different scenarios examined for Azungwu are shown in Figure 5 and Table 3. From Figure 5, it's clear that when looking at the Net Present Cost (NPC), case 2, which utilizes solar energy, stands out as the most cost-effective option. On the other hand, case 1, which relies solely on a diesel generator to meet demand, has a significantly higher initial capital cost about NGN4.5M, nearly double that of cases 2 and 3. This steep NPC is largely due to the high operating costs tied to diesel prices and generator maintenance. When we compare the working hours of the generator in cases 3 and 1, as shown in Table 3, we see that using PV technology reduces the operating hours by a factor of six, which is a positive outcome considering the reduction in emissions. In terms of operating hours, case 2 proves to be the most advantageous configuration among all scenarios (cases 1, 2, and 3), yielding the highest Renewable Factor (RF). Figure 5 also highlights that case 1, which is a stand-alone diesel setup, incurs the highest costs, resulting in a notably greater NPC compared to the other scenarios. The main distinction between scenario 2 and 3 lies in the power supplied by the diesel plant during the rainy season, when solar panels experience a significant drop in output due to reduced sunlight. Figure 6 gives a clear picture of how the solar panels and diesel generators performed over the year in the best setup for case 3. From the graph, you can see that during the sunnier months, roughly from October to February, the solar panels do most of the work, contributing the bulk of the electricity (Fabio et al, 2020). During these months, the diesel generator barely needs to kick in since the PV system handles most of the load. But when the rainy season hits, especially in May, June, and July, solar production drops drastically and barely makes a dent. To keep things running smoothly during this period, the diesel generator picks up the slack and compensates for the low solar output, ensuring a steady power supply all year round.

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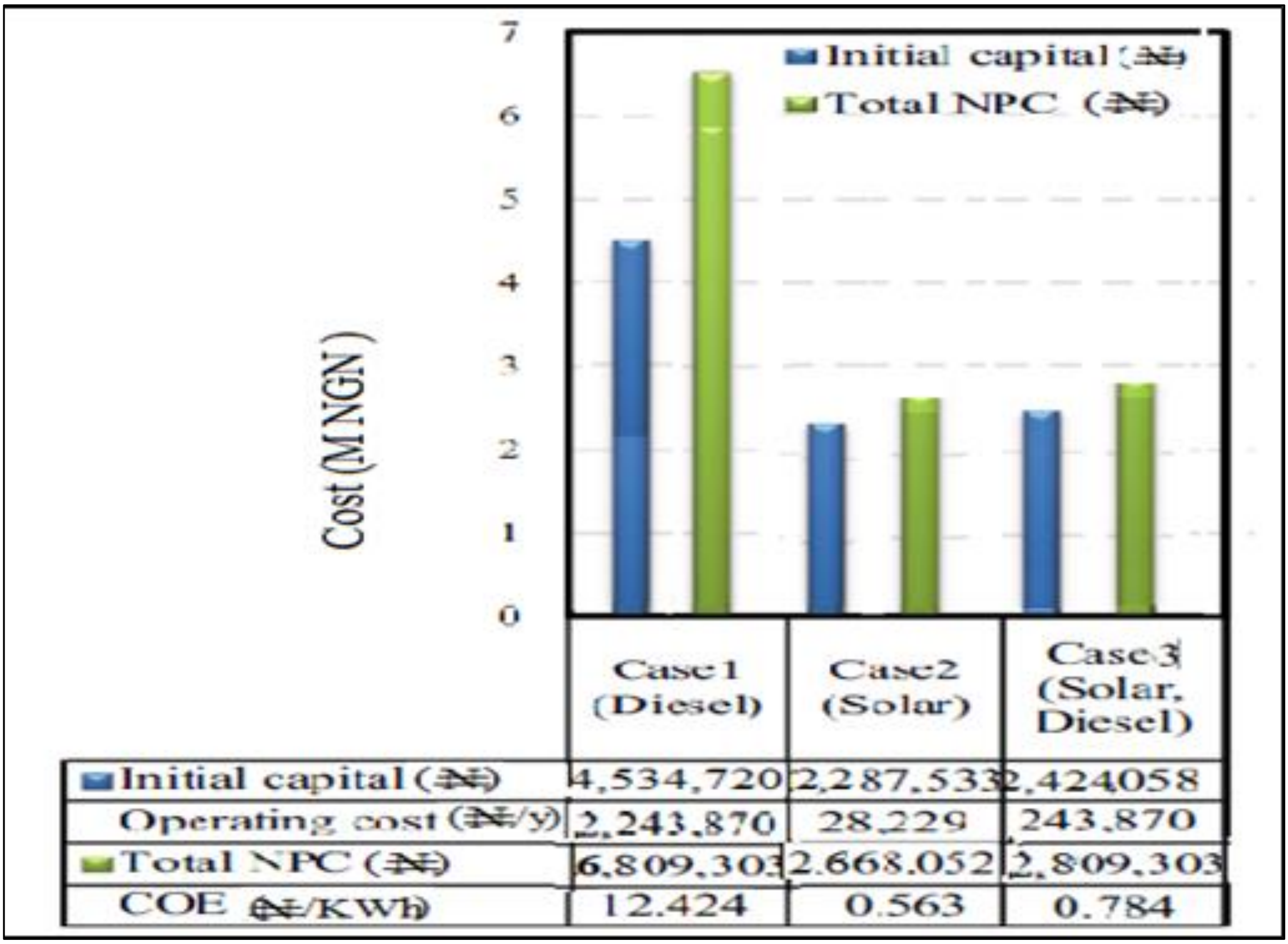

Fig 5 System Costs Associated With Each Case Investigated for Azungwa : ₦ NGN

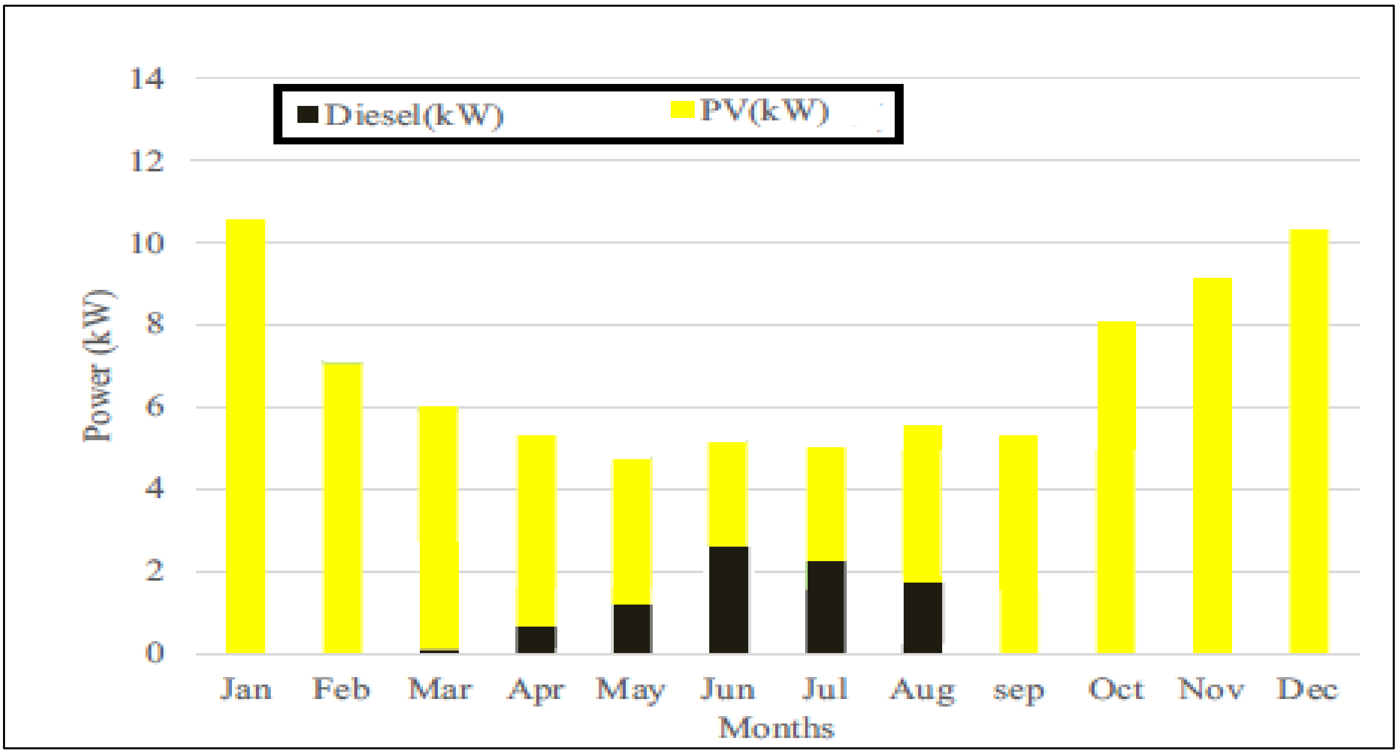

Fig 6 Total Power Generated in Case 3 for Azungwu

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➢ *Optimized Designs for Agidiase in Kwale Road*

Table 4 and Figure 7 present an enhanced results and the related costs for all the scenarios we evaluated for Agidiase. Looking at Table 4, it's easy to see how each configuration performs in terms of overall economic feasibility. Among the options, case 2 (solar-only) and case 3 (solar–diesel hybrid) stand out clearly. These two scenarios show the lowest Net Present Cost (NPC), making them the most cost-effective choices. This suggests that integrating solar, either alone or alongside diesel, offers a more economical solution compared to the other alternatives considered. In case 3, solar panels account for a whopping 87% of the total generation, while diesel generators contribute just 13%. Among these two low NPC cases, case 2 stands out as the most environmentally friendly option, achieving a 100% renewable fraction. Figure 7 further illustrates that, similar to the findings for Azungwu, case 2 not only has the lowest NPC but is also the most cost-effective setup. In contrast, case 3 incurs the highest initial costs compared to case 1, primarily due to the expensive diesel generators when stacked with renewable energy components. However, the long-term costs and carbon emissions associated with case 1 plan diminish its advantages. As shown in Table 4, the operating hours for the diesel generator in case 3 are roughly one-fiftieth of those in case 1.

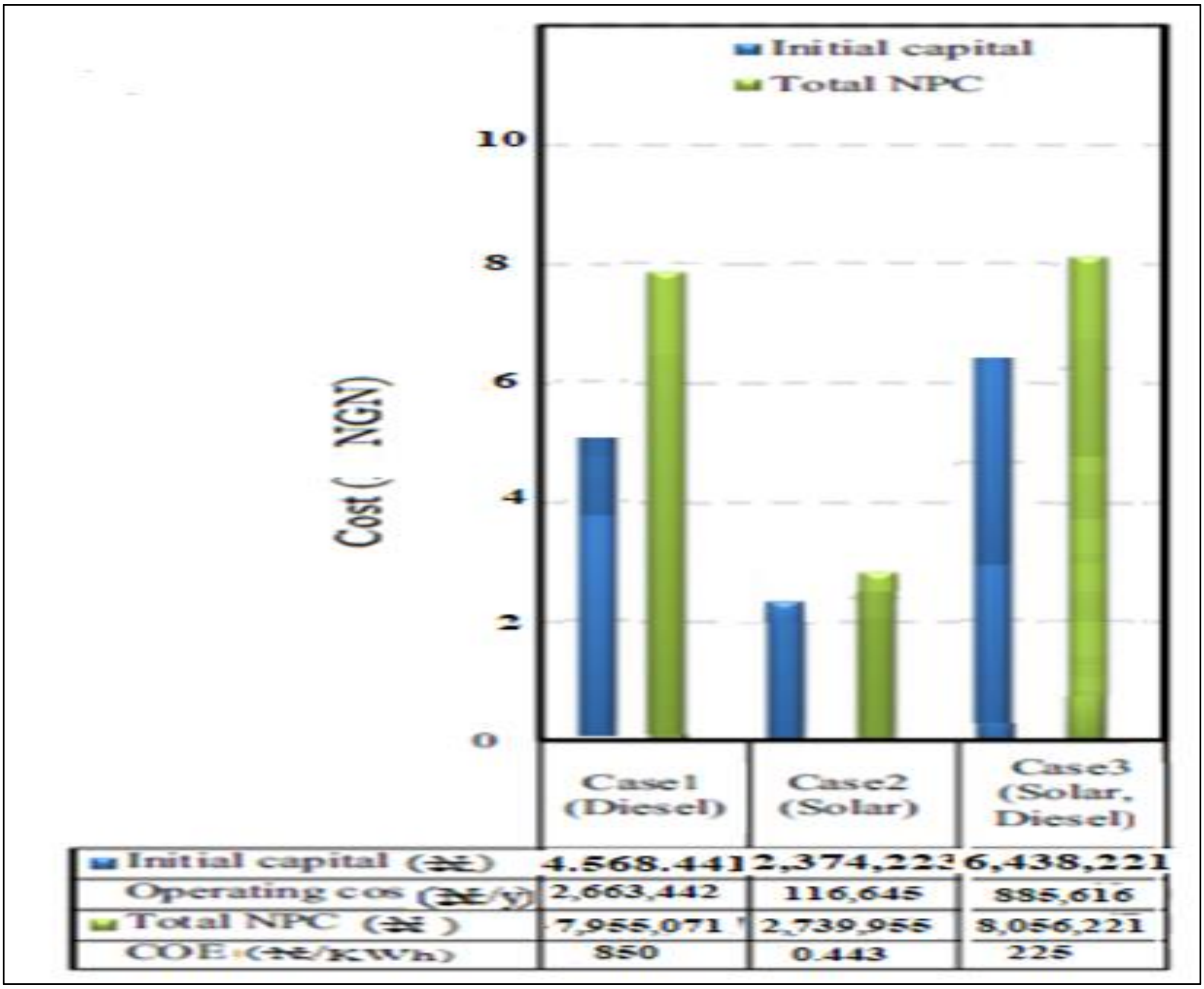

Fig 7 System Costs Associated with Each Investigated for Agidiase ₦

➢ *Optimized Designs for Agidiehe*

The best sizing options and their costs for Agidiehe, based on different scenarios, are detailed in Table 5 and illustrated in Figure 8. If you take a look at Figure 8, you'll notice that the two scenarios with the lowest Net Present Cost (NPC) are case 2 and case 3. Just like in previous regions, case 2 proves to be the most cost-effective choice among the hybrid systems. On the other hand, case 1 still has the highest initial cost, but case 2 ultimately results in the lowest NPC overall. In case 3, as shown in Table 5, diesel generators contribute just 5% to the total generation, while solar modules dominate with an impressive 95%. Case 2 really shines as the eco-friendliest setup, relying completely on a PV system. The carbon dioxide emissions from case 3 are significantly lower than those from case 1.

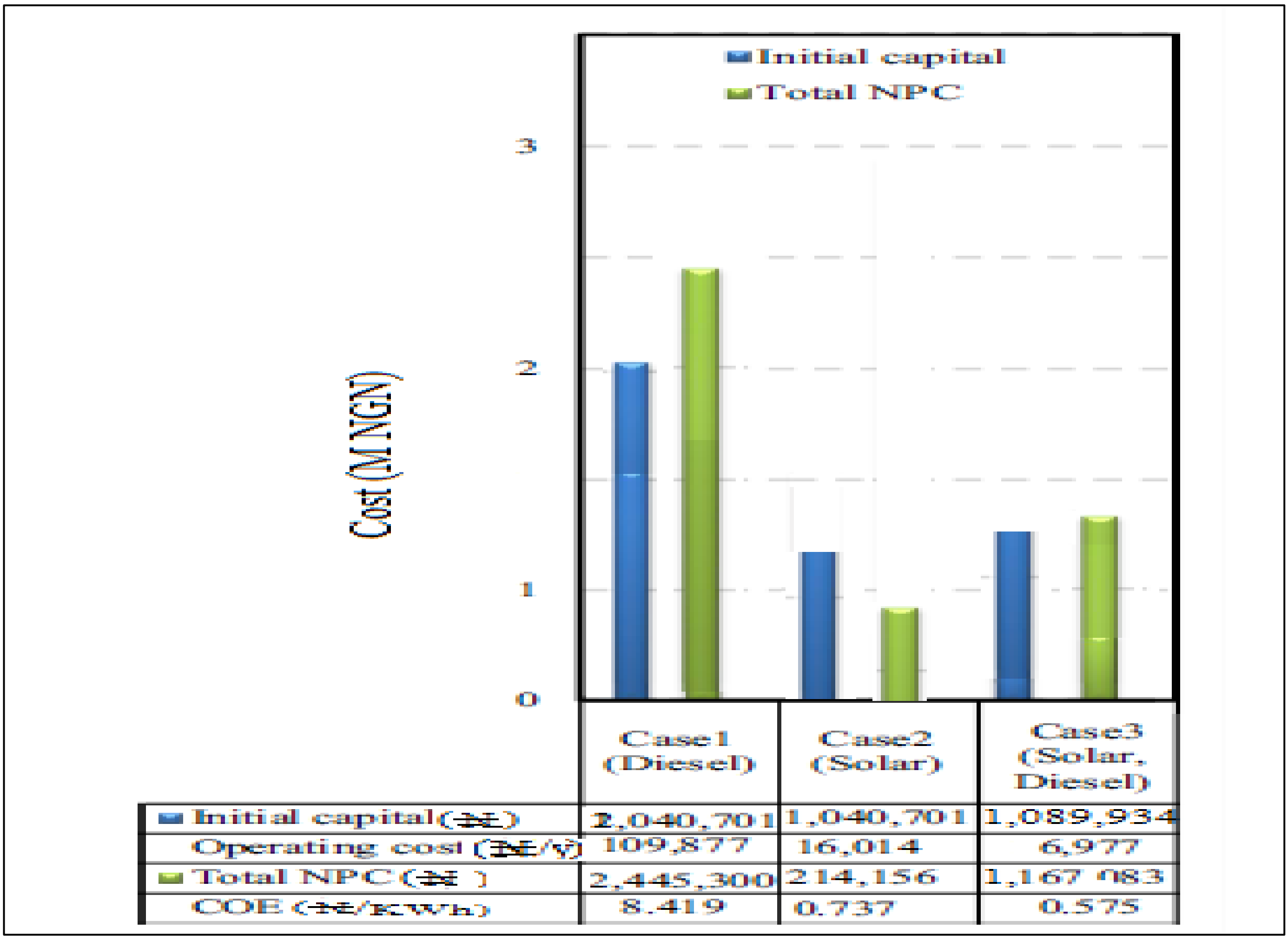

Fig 8 Sysytem Costs Associated with Case Investigated for Agidiehe: ₦ NGN

Table 4 The rated capacity of the main components in the best-performing hybrid system (case 3)

Location	PV (KW)	Generator (KW)	No of Battery	Converter
Azungwu	40	20	50	20
Agidiase	20	10	40	20
Agidiehe	50	10	30	10

VI. CONCLUSION

We took a close look at how well stand-alone power perform in off-grid communities across the different climate zones of Ogwashi-Uku. The goal was to see how reliable and practical these systems are under varying weather conditions. To find the best setup, we focused on minimizing the net present cost (NPC), and then we dug deeper into the chosen optimal systems by looking at other economic indicators and environmental factors. The findings revealed that, for all the communities we studied, the solar PV configuration stands out as the most economically viable option while the hybrid solar-diesel tends to be highly reliable. Specifically, in Azungwu, while a diesel-only system might seem cheaper at first requiring only about six times of the initial investment of the hybrid system and energy storage system, the hybrid option actually results in the lowest NPC over time. For the case of Azungwu, the optimal configuration requires an initial capital of NGN 4,534,720, and corresponds to an operating cost of 2,243,870 NGN/y, a total NPC of NGN 6,809,303 and a COE of 12.424 NGN/kWh. The best hybrid setup for Azungwu achieved an 88% renewable share, cutting CO_2 emissions down to just 6.1% of what the diesel-only system produces (74,391 kg of CO_2 per year). For the other locations, the comparison shows that the hybrid systems emit about 16% of the diesel-only emissions in Agidiase and roughly 13% in Agidiehe. The differences observed in the resulting ratios stem from variations in renewable energy resource availability and the load profiles of the studied locations. Community leaders in Ogwashi-Uku, together with the Nigerian government, enabling the adoption and implementation of these technologies in rural areas. Right now, the only support for renewable energy-based electricity generation plants in Ogwashi-uku comes from private sector participation a depreciation framework within the income tax system. Delta State in Nigeria is increasingly positioning itself to support renewable energy-based electricity generation, especially as part of broader efforts to expand access, attract investment, and transform its energy sector. While most of the specific support frameworks link with national programmes and state policy reforms. If we could roll out some solid incentive policies, we could really bring down the cost of energy (COE) for these systems, making it much more feasible for the communities we're targeting to adopt and install them.

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