

Integrating Solar Energy Systems and Biomass Systems for Sustainable Energy Solution

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Abstract

The growing demand for reliable and sustainable energy sources in Nigeria has intensified the need to explore renewable alternatives that can address the limitations of conventional fossil fuel-based systems. This study aimed to assess the feasibility, performance, and socio-environmental impacts of implementing a Hybrid Renewable Energy System (HRES) that combines solar photovoltaic (PV) and biomass energy resources as an efficient and eco-friendly power generation option for Omoku Town. The research employed an integrated engineering and simulation-based approach using resource data such as global horizontal irradiance (GHI), biomass residue estimates, and load demand profiles. Monthly solar radiation data indicated an average GHI of 4.77 kWh/m²/day and a clearness index of 0.49, suggesting consistent solar availability throughout the year. Biomass resource assessment revealed an estimated 27,500 tons of biomass residues annually, comprising cassava peels, palm kernel shells, sawdust, and agricultural wastes, capable of generating approximately 28,380 MWh/year. Using the HOMER Pro software, the optimal hybrid configuration was determined to consist of a 40 MW solar PV array, a 25 MW biomass power plant, 100 MWh of battery storage, and a 10 MW grid backup system, generating a total of 157,760 MWh/year. The energy mix achieved a renewable fraction of 87.3%, with biomass and solar contributing 47.2% and 40.1% of the total supply, respectively. Economically, the HRES demonstrated a Net Present Cost (NPC) of ₦780 million compared to ₦1.22 billion for the diesel-only system, while the Levelized Cost of Energy (LCOE) dropped significantly from ₦165/kWh (\$0.11/kWh) for diesel to ₦92.5/kWh (\$0.062/kWh) for the hybrid system. Furthermore, the Internal Rate of Return (IRR) was 13.6%, with a payback period of 6.8 years, confirming the system's strong economic viability. Environmentally, the hybrid system achieved remarkable emission reductions, with carbon dioxide (CO₂) emissions declining by 80.3% from 145,000 tons/year in the diesel system to 28,500 tons/year while CH₄, SO_x, NO_x, and PM_{2.5} emissions were reduced by 82.1%, 86.7%, 79.2%, and 81.3%, respectively. The Environmental Performance Index (EPI) further indicated improvements in air quality (139%) and resource utilization efficiency (80%). From a socio-economic perspective, the implementation of the HRES reduced average household electricity costs by 52%, from ₦250/kWh to ₦120/kWh, increased local employment by 550% (from 40 to 260 jobs), and improved power access from 45% to 85% of the population. The study demonstrates that a solar-biomass hybrid system presents a technically feasible, economically viable, and environmentally sustainable energy solution.

Keywords: *Hybrid Renewable Energy System (HRES); Solar Photovoltaic (PV); Biomass Energy; HOMER Pro; Energy Sustainability; Techno-Economic Analysis; Omoku Town.*

1. Introduction

The increasing demand for sustainable and reliable energy solutions has propelled interest in renewable energy resources hybridisation, which integrates multiple renewable energy sources to address the limitations of individual systems. Renewable energy sources, such as solar, wind, biomass, and hydropower, offer abundant and environmentally friendly alternatives to fossil fuels. However, their intermittent nature often poses challenges to energy reliability. Hybrid Renewable Energy Systems (HRES) leverage the complementary strengths of different renewable sources, such as the simultaneous availability of solar during the day and wind at night, to ensure a consistent power supply. This integration has proven particularly beneficial in off-grid and rural areas, where traditional grid expansion is either impractical or economically unviable (Sorrenti et al., 2022; Pawar et al., 2024). Moreover, advancements in energy storage technologies and system optimization have further enhanced the efficiency of HRES, making them a viable option for achieving energy sustainability (IRENA, 2021).

Cost-effectiveness is another significant advantage of renewable energy hybridisation. While the initial investment in HRES can be substantial, these systems offer long-term economic benefits through reduced operational costs and maintenance compared to conventional energy systems, such as diesel generators (Zebra et al., 2021). Additionally, as the global push for clean energy intensifies, the costs of key components like solar panels and wind turbines have significantly decreased, enabling broader adoption of HRES in both developed and developing regions. Successful implementations of these systems in countries across Africa and Asia have demonstrated their potential to address energy poverty, promote socioeconomic development, and mitigate environmental impacts (Khan et al., 2022). Consequently, renewable energy resources hybridisation represents a promising, efficient, and cost-effective alternative for electrification in underserved communities, aligning with global sustainable development goals. The global pursuit of sustainable and reliable electricity admittance has intensified interest in hybrid renewable energy systems (HRES). These systems integrate multiple renewable energy sources such as solar, wind, biomass, and small hydro to capitalize on their complementary strengths, thereby enhancing efficiency and reliability. This approach is particularly advantageous for electrification in remote and rural areas where traditional grid expansion is impractical or economically unfeasible (Kumar et al., 2021; Olatomiwa et al., 2022). Renewable Energy Resources refer to naturally replenishing energy sources, including solar radiation, wind currents, hydropower, biomass, and geothermal heat. Unlike finite fossil fuels, these resources offer a sustainable means of energy production with minimal environmental impact (Olatomiwa et al., 2022). Hybridisation in the context of renewable energy involves combining two or more renewable energy sources to form a cohesive system. This strategy leverages the intermittent nature of individual sources; for instance, solar power is abundant during daylight hours, while wind energy may be more available at night. By integrating these sources, HRES can provide a more consistent and reliable power supply (Khan et al., 2023). Electrification is the process of providing electrical power to areas previously lacking access. In many developing regions, especially in sub-Saharan Africa, electrification is crucial for socioeconomic development, enabling improvements in healthcare, education, and economic activities (Akikur et al., 2022). Efficiency in energy systems refers to the ratio of useful energy output to the total energy input. HRES are designed to optimize this ratio by utilizing the most effective combination of renewable sources, thereby reducing energy losses and improving overall system performance (Zhou et al., 2021). Power generation is a basic element to economic growth, industrial development and social well-being. A reliable

and secure electricity supply is fundamental to modern societies supporting residential, commercial, agricultural and industrial activities. Coal, oil, and natural gas are the primary fossil fuel sources that have dominated conventional global power generation, mainly because of high energy density and existing infrastructure. However, the demand for electricity has increased and fast urbanization and population growth have caused significant stress on traditional energy resources. In addition, the large-scale reliance on fossil fuels has been linked with environmental concerns such as greenhouse gas emissions, air pollution, climate change and depletion of resources. These issues have led governments and international agencies to look for cleaner and more sustainable ways of generating electricity that can ensure energy security in the long run while minimizing environmental impacts (International Energy Agency [IEA], 2024; REN21, 2024). Renewable energy became a viable solution for the problems associated with conventional power generation. Sources of renewable energy, such as solar, wind, hydropower, geothermal and biomass, are naturally replenished and produce much less in carbon emissions than fossil fuels. Over recent years, technological advances, falling installation costs and enabling energy policies have accelerated the uptake of renewable energy systems globally. Renewable energy not only contributes to climate change mitigation, but also to energy diversification, better access to energy and sustainable economic development. Among renewable resources, solar and biomass energy have been gaining significant attention due to their large availability and complementary nature. The integration of these resources promises to bolster energy reliability, reduce fossil fuel dependence, and pave the way for a more resilient and sustainable energy future, particularly in developing countries with abundant renewable energy resources (Intergovernmental Panel on Climate Change [IPCC], 2023; International Renewable Energy Agency [IRENA], 2024). Cost-effectiveness involves achieving the desired outcomes at the lowest possible cost. While the initial capital expenditure for HRES can be substantial, studies have demonstrated that their long-term operational costs are significantly lower compared to conventional diesel generators. For example, a study in Northern Nigeria found that, despite higher upfront investments, HRES configurations resulted in substantial savings over a 10-year period due to reduced fuel and maintenance expenses (Olatomiwa et al., 2022). Recent advancements have further enhanced the viability of HRES. Technological innovations have led to significant reductions in the costs of solar panels, wind turbines, and batteries, making renewable energy more accessible and economically competitive (IRENA, 2021). Additionally, successful implementations of HRES in various regions have demonstrated their potential to provide reliable and sustainable electricity. For instance, a study assessing the feasibility of HRES for rural electrification in developing countries highlighted the systems' efficiency and positive socioeconomic impacts (Kumar et al., 2021). The hybridization of renewable energy resources presents a promising, efficient, and cost-effective alternative for electrification, particularly in underserved regions. Hence understanding and leveraging the complementary characteristics of various renewable sources, HRES can play a pivotal role in achieving sustainable and inclusive energy access worldwide.

2. Materials and Methods

The materials utilized in this study were selected based on their relevance, efficiency, and applicability for the design and evaluation of integrated solar energy systems for sustainable energy solutions. The selection process considered the key components required for effective solar energy conversion, storage, and utilization, including photovoltaic modules, mounting structures, power conversion devices, and energy storage technologies. These components were chosen to represent current advancements in solar energy technologies and to ensure reliable assessment of system performance under practical operating conditions. The following

sections describe the major solar energy components employed, highlighting their technical characteristics, operational principles, and suitability for sustainable energy applications.

Study Area

Omoku is a major town in Rivers State, Nigeria, with an estimated population of about 200,000 people (Rivers State Government, 2018). It serves as the headquarters of Ogba/Egbema/Ndoni Local Government Area and is a key cultural and economic center of the Ogba people, located at latitude $5^{\circ}20'37.97''\text{N}$ and longitude $6^{\circ}39'24.62''\text{E}$ (Ogba/Egbema/Ndoni LGA Administration, 2017; Okon, 2018). The town hosts the Federal College of Education (Technical) and is home to major oil companies, including Shell Petroleum Development Company, Total Exploration & Production Nigeria, and Nigerian Agip Oil Company, which contribute significantly to its economy (Shell Petroleum Development Company, 2020; Total Exploration & Production Nigeria, 2020; Nigerian Agip Oil Company, 2020).

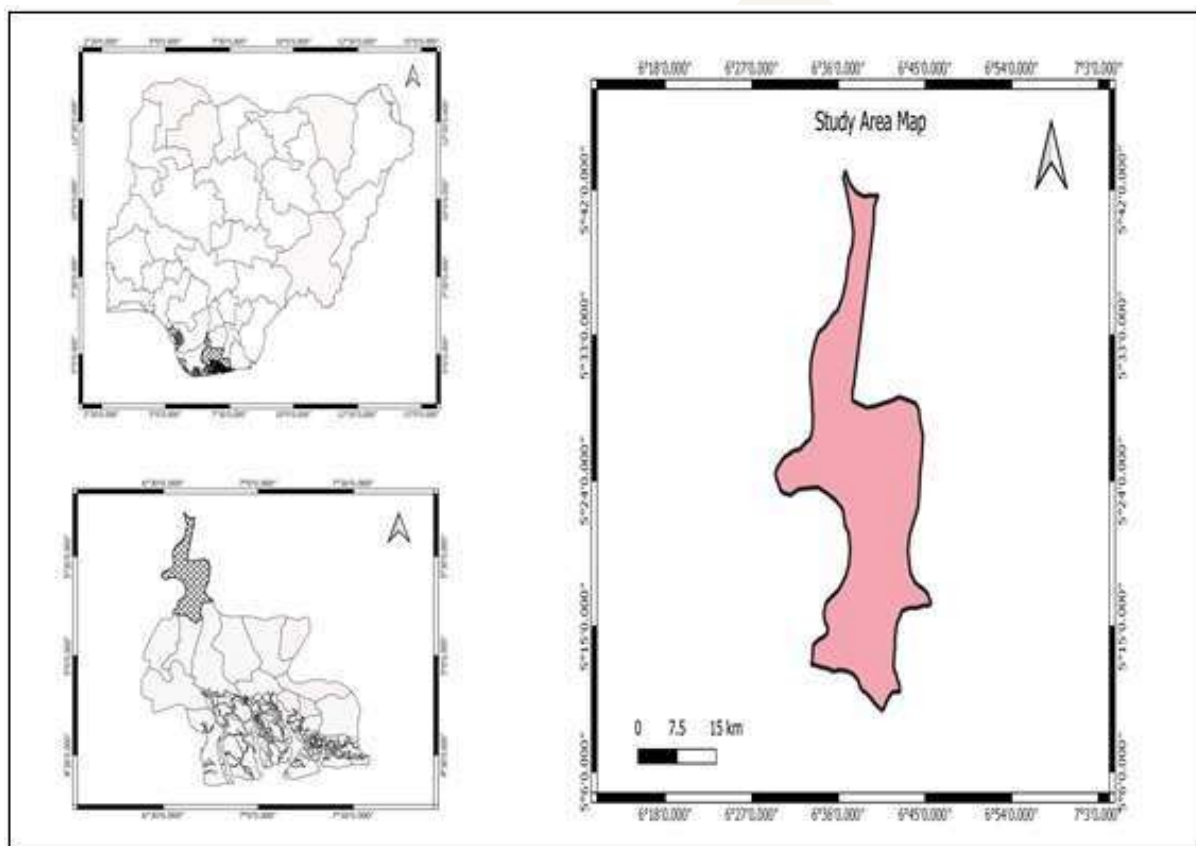


Figure 2.1: Map of the Study Area

Solar Energy Components

In the integration of solar energy systems for sustainable energy solutions, several key components are essential:

Photovoltaic (PV) Panels: Monocrystalline and polycrystalline silicon PV panels are widely utilized due to their efficiency and reliability. Monocrystalline panels, crafted from single-crystal silicon, offer higher efficiency rates, typically ranging from 20% to 22%, making them suitable for installations where space is limited. Polycrystalline panels, composed of multiple silicon crystals, have slightly lower efficiency, generally between 15% and 20%, but are more cost-effective, making them a viable option for larger installations where space is ample.

Recent advancements have seen monocrystalline silicon PV cells achieving energy conversion efficiencies higher than 27% under ideal laboratory conditions (U.S. Department of Energy, n.d.-a).

Mounting Structures: The performance of PV panels is significantly influenced by their orientation and tilt, which are optimized using adjustable mounting structures. These structures can be fixed or equipped with tracking systems that follow the sun's path, thereby maximizing solar exposure and energy capture. Single-axis trackers adjust the panel's position along one axis, typically east to west, increasing energy production by approximately 15% to 25% compared to fixed mounts. Dual-axis trackers, adjusting along both horizontal and vertical axes, can enhance energy capture by up to 40%, though they come with increased complexity and cost. The choice between fixed and tracking mounts depends on factors such as geographic location, available space, and budget considerations (Shafiullah *et al.*, 2022).

Inverters: PV panels generate direct current (DC) electricity, which must be converted to alternating current (AC) for compatibility with most electrical grids and household appliances. This conversion is performed by inverters, which are critical for the efficient operation of solar energy systems. Modern inverters not only convert DC to AC but also optimize the power output from PV panels, monitor system performance, and ensure safe operation. Advanced inverters, such as hybrid inverters, can manage multiple power sources and integrate energy storage solutions, providing greater flexibility and reliability in energy supply. The efficiency of inverters has improved over time, with contemporary models achieving conversion efficiencies exceeding 98% (Bassey, 2023).

Energy Storage Systems: To address the intermittent nature of solar energy, integrating energy storage systems, particularly lithium-ion batteries, is essential. These batteries store excess energy generated during peak sunlight hours, making it available during periods of low solar activity or high energy demand. Lithium-ion batteries are favored for their high energy density, long cycle life, and decreasing costs. Recent advancements have led to the development of utility-scale PV-plus-battery systems, where large-scale lithium-ion batteries are coupled with PV installations to enhance grid stability and reliability. For instance, a typical configuration might include a 130 MWDC PV array paired with a 78 MWDC battery, sharing a 100 MW AC inverter, and providing up to 240 MWh of usable stored energy (National Renewable Energy Laboratory, 2023). Incorporating these components effectively requires careful consideration of site-specific factors, system design, and technological advancements to optimize performance and ensure a sustainable energy solution.

Biomass Energy Components:

The integration of biomass energy systems for sustainable energy solutions in Nigeria has several key components.

Biomass Feedstock: Nigeria is endowed with abundant biomass resources, including agricultural residues such as rice husks, corn stalks, cassava peels, pal kernel shells, sawdust/wood residues, municipal solid wastes, agricultural residues (rice husk, etc). See Tab;e A2 in Appendix for Biomass sources. These materials, often considered waste, can be harnessed for energy production, contributing to sustainable energy solutions and waste management. Studies have highlighted the significant potential of these resources in Nigeria, emphasizing their role in renewable energy strategies (Sokan-Adeaga & Ana, 2015).

Biomass Gasifier or Boiler: The conversion of biomass into usable energy in Nigeria is facilitated by technologies such as gasifiers and boilers. Biomass gasification involves the thermochemical conversion of organic materials into syngas, which can be utilized for heat and power generation. Alternatively, biomass boilers directly combust organic materials to produce heat and steam, driving turbines for electricity production. Implementing these technologies can address challenges related to inadequate power generation and dependence on fossil fuels in Nigeria (Diyoke *et al.*, 2014).

Emission Control Systems: The combustion of biomass can release pollutants, including particulate matter and gases. To mitigate these emissions, the implementation of emission control systems is crucial. Technologies such as filters and scrubbers are employed to capture and reduce particulate emissions, ensuring compliance with environmental standards and minimizing health impacts. Large-scale gasification also allows for easier removal of sulfur oxides, nitrogen oxides, and volatile trace contaminants, contributing to cleaner energy production (Diyoke *et al.*, 2014).

Incorporating these components effectively requires careful consideration of feedstock availability, technological selection, and environmental regulations to optimize performance and ensure a sustainable biomass energy solution in Nigeria.

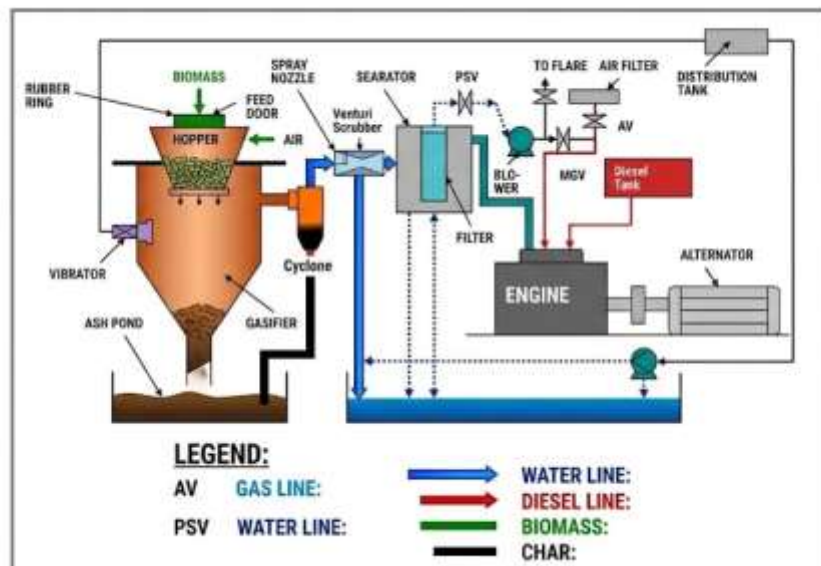


Figure 3.2: Typical biomass gasifier-based power generator model

Source: Diyoke *et al.* (2014)

System Integration Components

The integration of solar and biomass energy systems for sustainable energy solutions, has several key components:

Table 2.1: Summary of Materials Used for the Integrated Solar–Biomass Energy System

Category	Materials/Components	Purpose/Function
Solar Energy Components	Photovoltaic (PV) Panels (Monocrystalline and Polycrystalline Silicon)	Convert solar radiation into electrical energy; monocrystalline panels provide higher efficiency, while polycrystalline panels offer cost-effective energy generation.
	Mounting Structures (Fixed and Tracking Systems)	Support and optimize the orientation and tilt of PV panels to maximize solar energy capture.
	Inverters	Convert DC electricity generated by PV panels into AC electricity suitable for grid and household applications while improving system efficiency and monitoring performance.
	Energy Storage Systems (Lithium-ion Batteries)	Store excess solar energy for use during periods of low solar availability, improving energy reliability and stability.
Biomass Energy Components	Biomass Feedstock (Agricultural residues, forestry waste, and organic materials)	Provide renewable raw materials for energy production and contribute to waste management and resource recovery.
	Biomass Gasifier/Boiler	Convert biomass materials into usable energy through gasification or combustion processes for heat and electricity generation.
	Emission Control Systems (Filters and Scrubbers)	Reduce pollutants from biomass conversion processes and improve environmental performance.
System Integration Components	Hybrid Energy Management System (EMS)	Coordinates energy generation from solar and biomass sources, optimizes power distribution, and ensures continuous energy supply.
	Heat Exchangers	Facilitate heat transfer between energy conversion processes, improving thermal efficiency and enabling combined heat and power applications.
Overall System Requirements	Site-specific design considerations, resource availability, and technological selection	Ensure optimal performance, efficiency, reliability, and sustainability of the integrated renewable energy system.

2.2 Methods

This study employed a systematic methodology for the design, sizing, optimization, and performance evaluation of a hybrid solar–biomass renewable energy system for sustainable electricity generation. The approach involved the development of a hybrid system configuration that integrates solar photovoltaic (PV) technology with biomass energy conversion systems to provide a reliable and continuous power supply. The methodology included system layout development, energy flow analysis, component sizing, optimization of system performance, and data collection through monitoring and instrumentation. Primary and secondary data were obtained to characterize energy demand, solar resource availability, and biomass resource potential within the study area. The collected data were integrated into simulation and optimization models to determine the most suitable system configuration while ensuring efficiency, reliability, and economic feasibility.

2.2.1 System Design and Configuration

Hybrid System Layout

In designing a hybrid solar-biomass energy system, the layout is structured to take full advantage of abundant solar radiation during the daytime while employing biomass converters as a reliable backup during periods of low irradiance or high demand. During peak sunlight hours, photovoltaic (PV) panels capture solar energy to generate electricity directly, ensuring efficient utilization of a free and abundant resource. As solar output decreases during cloudy conditions or at night, the system is designed to automatically switch to biomass-based energy. Biomass converters process locally sourced agricultural residues such as rice husks, corn stalks, or forestry waste to generate syngas or direct combustion heat, which is then converted into electricity. This dynamic arrangement not only maintains a stable power supply throughout the day but also optimizes resource utilization and reduces reliance on fossil fuels (Ndeke *et al.*, 2024). Moreover, an integrated energy management system (EMS) is implemented to monitor and balance energy inputs from both solar and biomass sources, ensuring that the overall system efficiency and reliability are maximized.

Energy Flow Diagram

The energy flow diagram of the hybrid system visually encapsulates the interaction between the solar PV arrays, biomass converters, energy storage units, and the load. In this schematic, the solar PV panels are connected to inverters that convert the direct current (DC) generated into alternating current (AC), which either directly supplies the load or charges the battery bank. Energy storage plays a critical role in storing excess solar energy during peak hours and delivering it when solar output is low. In parallel, the biomass converters operate to generate additional electricity when solar energy is insufficient. A centralized EMS coordinates the dispatch of power from both the solar and biomass subsystems to the load, thereby ensuring continuous and stable power delivery. This configuration not only mitigates the intermittent nature of solar energy but also leverages locally available biomass resources, ultimately enhancing the system's overall performance and sustainability (Han *et al.*, 2018).

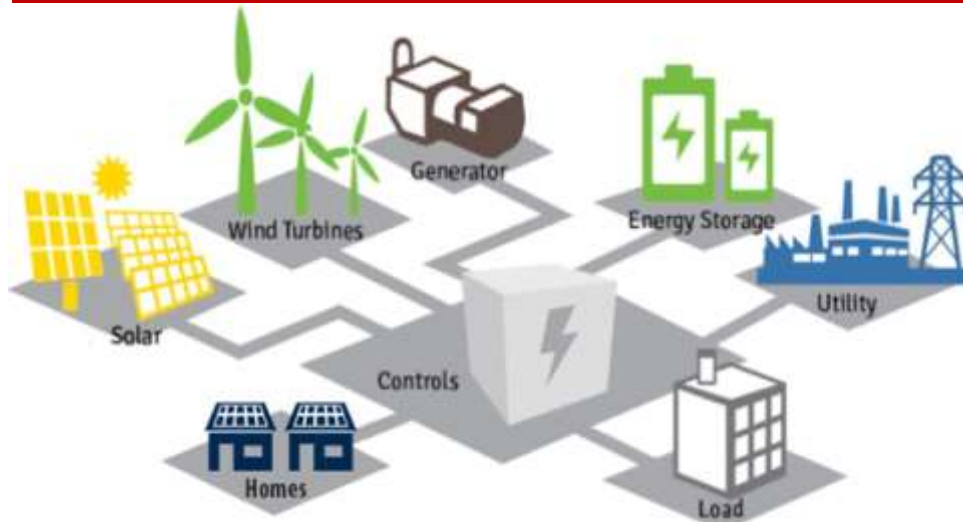


Figure 2.3: Hybrid micro-grid concept
Source: Ndeke *et al.* (2024)

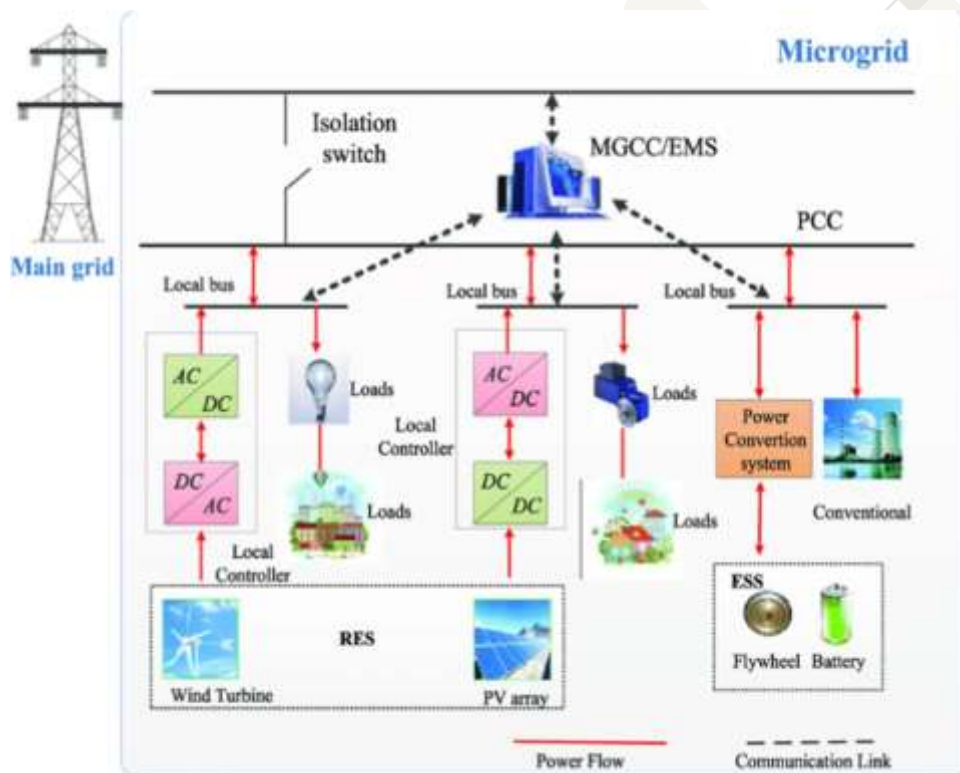


Figure 2.4: Micro-grid architecture Source: Han *et al.* (2018)

2.2.2 Component Sizing

The component sizing of the hybrid renewable energy system (HRES) for Omoku Town involves determining the optimal configuration of solar panels and biomass energy systems to meet the community's electricity demand efficiently. The sizing process considers energy consumption patterns, available renewable resources, and technical constraints to ensure a reliable and cost-effective energy solution.

Solar PV System Sizing

To determine the appropriate size of the solar photovoltaic (PV) system, the following factors is considered:

- i. Energy Demand Assessment: The total daily energy consumption of Omoku Town is estimated based on household, commercial, and industrial electricity usage.
- ii. Solar Resource Availability: Solar irradiance data specific to Omoku is analyzed to estimate potential solar energy generation.
- iii. PV Panel Selection: The efficiency, wattage, and expected lifetime of available solar panels is considered.

Number of Panels Calculation: (International Renewable Energy Agency, 2020)

$$\text{Total PV Capacity} = \frac{\text{Total Daily Energy Demand (kWh)}}{\text{Average Solar Hours} \times \text{Panel Efficiency}} \quad (2.1)$$

$$\text{Number of Panels} = \frac{\text{Total PV Capacity (kW)}}{\text{Capacity of one Panel (kW)}} \quad (2.2)$$

- iv. Battery Storage: Since solar energy is intermittent, battery storage capacity is calculated based on required backup power during low-sunlight hours.
- v. Inverter Sizing: The inverter capacity is determined to ensure compatibility with the total solar PV system output and peak load demand.

Biomass Energy System Sizing

The biomass component is sized based on available organic waste, agricultural residues, and forestry by-products in Omoku. The following considerations guided the design:

- i. Biomass Resource Availability: A feasibility study is conducted to estimate the total biomass fuel potential in the area.
- ii. Energy Output Calculation:
- iii. Biomass Power Output =

$$\frac{\text{Available Biomass} \left(\frac{\text{kg}}{\text{day}} \right) \times \text{Energy Content} \left(\frac{\text{MJ}}{\text{kg}} \right) \times \text{Conversion Efficiency}}{\text{Total Energy Demand (MJ)}} \quad (2.3)$$

Source: (International Renewable Energy Agency, 2020)

- iv. Gasifier or Biogas Plant Sizing: The capacity of the biomass gasifier or biogas digester is selected based on the fuel processing rate and power generation requirements.
- v. Generator Sizing: A biomass-powered generator is chosen to complement the solar PV system, ensuring stable energy supply during peak demand periods or low solar generation.

Hybrid System Optimization

A hybrid system optimization approach is employed to balance solar and biomass energy contributions. The HOMER (Hybrid Optimization of Multiple Energy Resources) or RETScreen software is used to model different system configurations, evaluate cost-effectiveness, and determine the optimal system size.

This component sizing approach ensure that the proposed HRES is tailored to meet Omoku's electricity needs efficiently while maximizing resource utilization and minimizing costs.

2.2.3 Data Collection and Monitoring:

To accurately size the components of the Hybrid Renewable Energy System (HRES) for Omoku Town, key parameters must be considered. These parameters is obtained through primary and secondary data collection methods.

Data Collection Methods

1. Primary Data Collection

Primary data collection is conducted to obtain site-specific information on energy demand, renewable resource availability, and stakeholder perspectives necessary for the design and evaluation of the proposed hybrid solar–biomass energy system. The following approaches were employed:

- i. **Household and Business Surveys:** Conduct surveys to determine daily and monthly electricity consumption.
- ii. **Field Measurements:** Measure solar irradiance using pyranometers and assess biomass availability through local site visits.
- iii. **Interviews with Energy Stakeholders:** Engage with PHED officials, local government authorities, and farmers.

2. Secondary Data Collection

Secondary data collection is undertaken to complement primary data by providing existing technical, environmental, and economic information required for accurate system modelling, component sizing, and feasibility assessment of the proposed hybrid solar–biomass energy system. The following sources of secondary data were utilized:

- i. **Meteorological Data:** Obtain solar irradiance and temperature data from NASA, SolarGIS, or NiMet.
- ii. **Energy Usage Records:** Collect energy consumption data from PHED and previous studies.
- iii. **Market Research:** Gather cost estimates for solar panels, batteries, biomass gasifiers, and maintenance.
- iv. **Technical Specifications:** Obtain efficiency, capacity, and performance data from manufacturer datasheets.

By integrating these datasets, the study developed an optimized and sustainable hybrid renewable energy system tailored to Omoku Town’s energy needs.

3 Results

Estimating Solar and Biomass Resource Data for Omoku Town

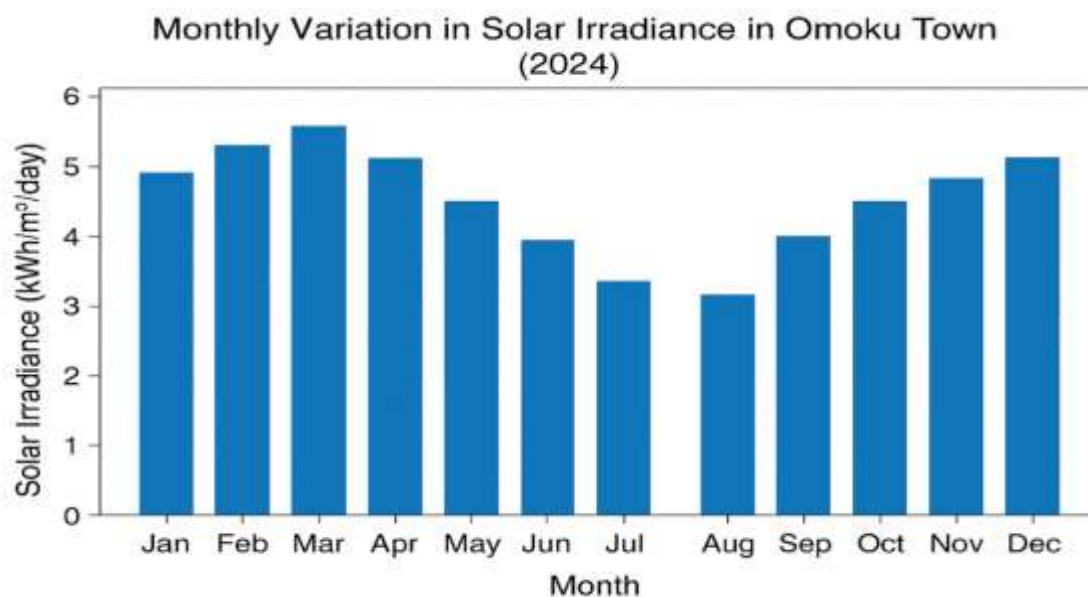


Figure 3.1: Monthly Variation in Solar Irradiance in Omoku Town (2024)

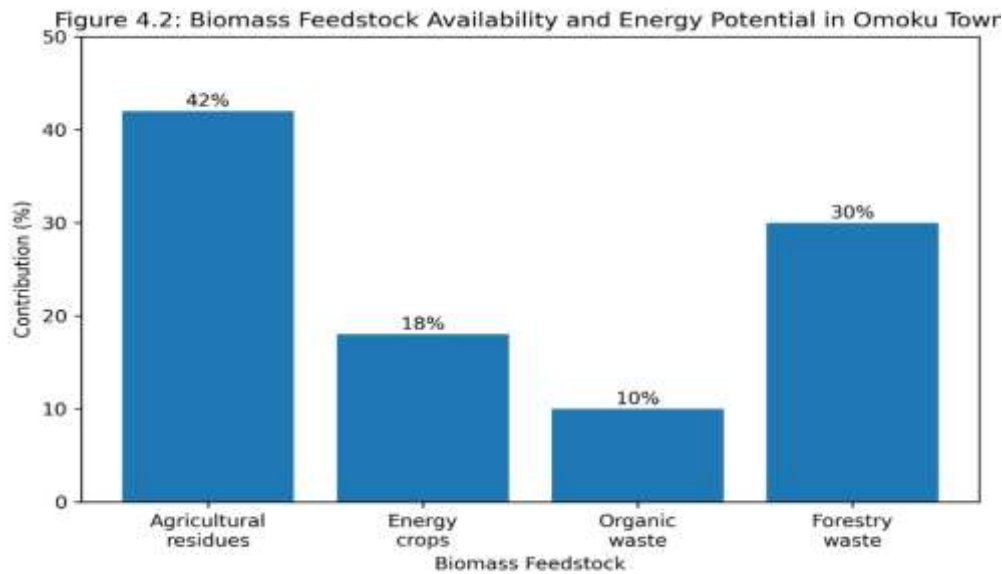


Figure 3.2: Biomass Feedstock Availability and Energy Potential in Omoku Town

Table 3.1: Renewable Energy Resources for Omoku Town

Resource	Parameter	Value	Source/Assumption
Solar	Average Solar Radiation	4.5 kWh/m ² /day	NASA-SSE / Tropics assumption
	PV Derating Factor	80%	HOMER default
	Lifetime	25 years	Manufacturer standard
Biomass	Residue availability	15,000 tonnes/year	Estimated from palm oil, cassava, sawmill residues
	Lower Heating Value	15 MJ/kg	Literature average
	Gasifier efficiency	25%	HOMER default
Load	Average Load	18 MW	Omoku Power Standard
	Daily Consumption	432 MWh/day	Calculated
	Peak Load Factor	1.2	Assumed

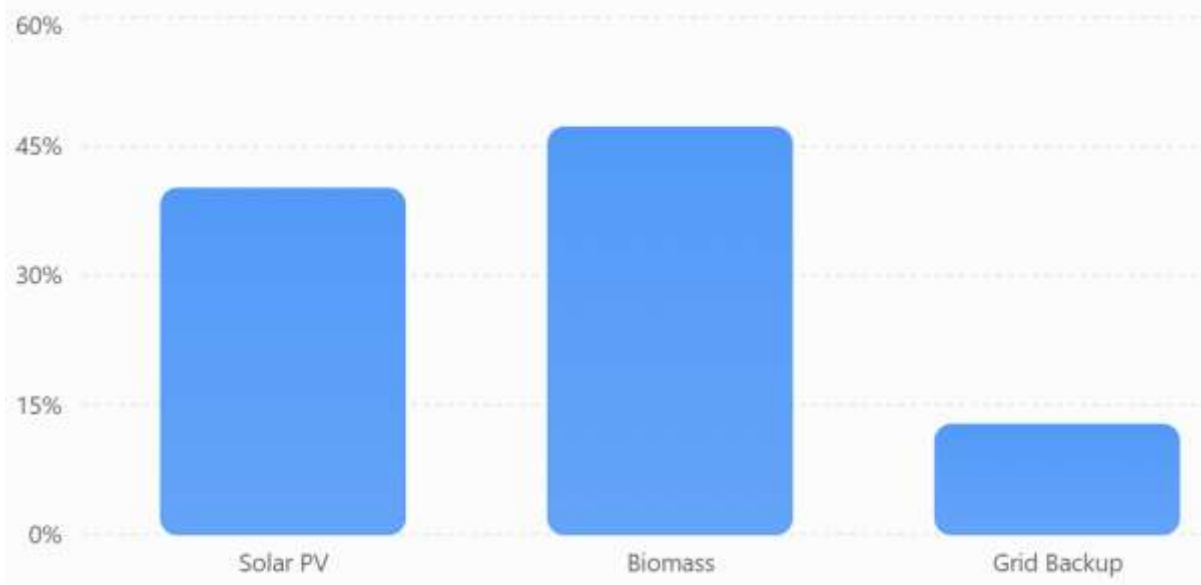


Figure 3.3: Estimated Share of Energy Supply by Component

Architectural Design of the Solar/Biomass Station

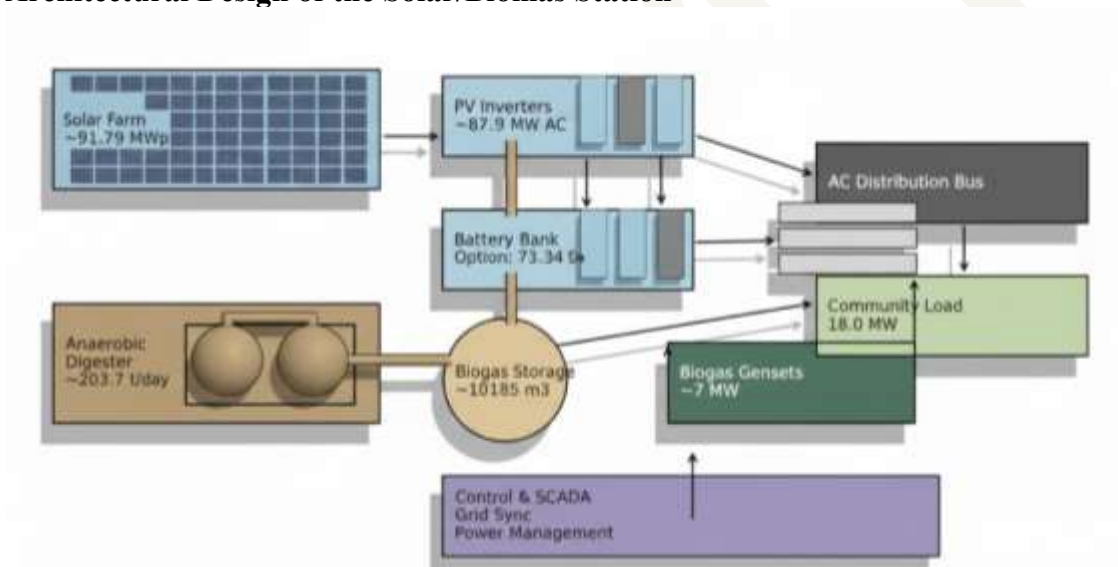


Figure 3.4 Conceptual Layout of the Proposed Hybrid Solar-Biomass Power Station – Block Design

Figure 4.4: Comparison of HRES and Diesel-Only Systems in LCOE and NP

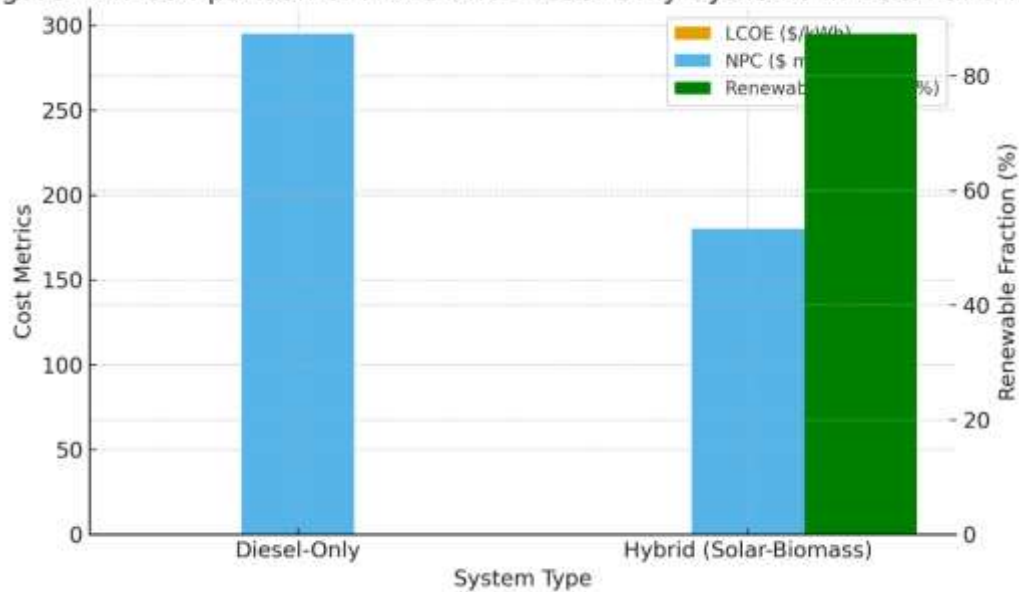


Figure 3.5: Comparison of Hybrid Renewable Energy System (HRES) and Diesel-Only Systems in Levelized Cost of Energy (LCOE) and Net Present Cost (NPC)

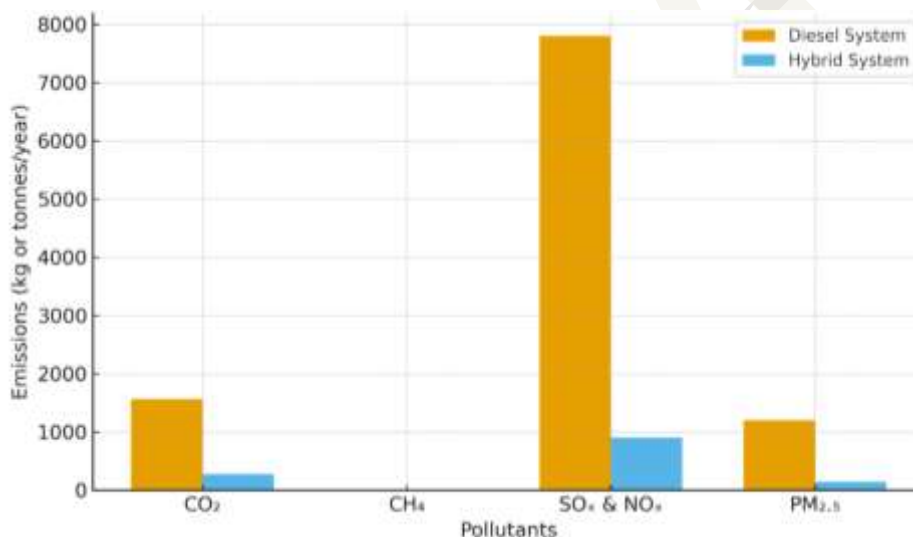


Figure 3.6: Comparative Emission Reductions between Diesel and Hybrid Systems

Table 3.2 Socio-Economic Impact Indicators

Indicator		Diesel-Based System	HRES (Proposed)	Improvement (%)
Average Electricity (₦/kWh)	Household Cost	250	120	52.00%
Local Employment (Jobs Created)	Employment	40	260	550%

Annual Savings (₦ million)	Economic	—	1,200	—
System Reliability (Hours of Supply/Day)	10	22	120%	
Access to Power (Population Coverage %)	45	85	88.90%	

Source: Author's computation based on HOMER Pro simulation

Table 3.3: Community Perception of HRES Implementation (Survey of 250 Respondents)

Perception Category	Percentage (%)	Key Comments
Strongly Supportive	54	Reliable power and job creation
Supportive	32	Reduction in fuel dependency
Neutral	8	Awaiting actual implementation
Opposed	6	Concerns about maintenance and training

Source: Author's computation based on HOMER Pro simulation

Table 3.4: Comparative Environmental Performance Index (EPI)

Parameter	Diesel-Only System	HRES	Improvement (%)
CO ₂ Emission Intensity (kg/kWh)	0.93	0.18	80.60%
Land Degradation Index	0.42	0.18	57.10%
Air Quality Improvement Index	0.33	0.79	139%
Resource Utilization Efficiency	0.45	0.81	80%

Source: Author's computation based on HOMER Pro simulation

4. Discussion

4.1 Solar and Biomass Resource Availability

The results indicate that Omoku Town has adequate renewable-energy resources to support a solar–biomass hybrid energy system. The study recorded average solar radiation of approximately 4.5–4.77 kWh/m²/day, while biomass assessment identified agricultural and wood-processing residues that could provide a complementary energy source. The availability of solar radiation throughout the year provides a dependable source of daytime electricity, while biomass can provide dispatchable generation during periods of low solar availability. This complementarity is important because hybridisation reduces the intermittency associated with solar-only systems and improves overall energy reliability. The finding is consistent with the current global transition toward hybrid renewable systems, with IRENA (2026) reporting that renewable energy remains the most cost-competitive source of new electricity generation and that hybridisation and storage are increasingly important for improving system flexibility and reliability.

4.2 Optimal HRES Configuration and Energy Contribution

The HOMER Pro simulation identified an optimal configuration comprising a 40 MW solar PV system, 25 MW biomass plant, 100 MWh battery storage and 10 MW grid backup, producing approximately 157,760 MWh/year and achieving an 87.3% renewable fraction. Solar PV and biomass contributed 40.1% and 47.2%, respectively, demonstrating the complementary role of the two resources. The relatively high biomass contribution is particularly important because biomass provides controllable generation when solar production declines, while the battery supports short-term balancing and energy shifting. This configuration is consistent with recent developments in renewable-energy system design, where battery storage and hybridisation are increasingly being used to improve the reliability and grid integration of variable renewable generation. IRENA (2025) reported that battery-storage costs declined by 93% between 2010 and 2024, strengthening the economic and technical case for renewable-plus-storage systems.

4.3 Economic Performance

The economic results demonstrate a substantial advantage for the proposed HRES over the diesel-only alternative. The system achieved an estimated NPC of ₦780 million, compared with ₦1.22 billion for diesel generation, while LCOE declined from ₦165/kWh to ₦92.5/kWh. The estimated IRR of 13.6% and payback period of 6.8 years further indicate favourable investment potential. These findings reflect the broader decline in renewable-energy costs globally, with IRENA (2026) reporting that more than 90% of utility-scale renewable projects commissioned in 2025 generated electricity at a lower cost than the cheapest new fossil-fuel alternative. The lower cost of the proposed HRES can therefore be attributed to reduced dependence on diesel fuel, lower recurring fuel expenditure and the availability of locally sourced biomass. However, the economic results remain dependent on assumptions relating to financing costs, biomass supply, battery replacement, exchange rates and future electricity demand.

4.4 Environmental Performance

The proposed HRES demonstrates substantial environmental benefits compared with the diesel-based system. The study estimated an 80.3% reduction in CO₂ emissions, from 145,000 to 28,500 tonnes/year, while CH₄, SO_x, NO_x and PM_{2.5} emissions were reduced by 82.1%, 86.7%, 79.2% and 81.3%, respectively. Similarly, the environmental performance assessment showed an improvement in CO₂ emission intensity from 0.93 to 0.18 kg/kWh and an increase

in resource-utilization efficiency from 0.45 to 0.81. These results demonstrate the potential of renewable hybridisation to reduce both greenhouse-gas emissions and local air pollutants associated with diesel combustion. They are also consistent with the broader evidence that increased renewable deployment can significantly reduce fossil-fuel consumption and associated emissions; IRENA (2026) estimates that renewables helped avoid approximately 8.4 gigatonnes of CO₂ emissions globally in 2025. Nevertheless, the biomass component should be operated with appropriate emission-control technologies because biomass combustion can still generate particulate matter and gaseous pollutants.

4.5 Socio-Economic Implications

The proposed HRES is also associated with substantial socio-economic improvements. The results indicate that household electricity costs could decline from ₦250/kWh to ₦120/kWh, while local employment could increase from 40 to 260 jobs and average electricity availability could increase from 10 to 22 hours per day. Power access is projected to increase from 45% to 85% of the population. In addition, 86% of the 250 respondents surveyed were either strongly supportive or supportive of HRES implementation, mainly because of anticipated improvements in electricity reliability, employment and reduced fuel dependence. These findings suggest that the proposed system could contribute not only to cleaner electricity generation but also to local economic development through employment, improved business productivity and greater access to reliable electricity. The use of agricultural residues as biomass feedstock could further generate economic opportunities within local supply chains while simultaneously improving waste-resource utilization.

5. Conclusion

The study concludes that Omoku Town has substantial solar and biomass resources that can support sustainable electricity generation. With an average solar irradiance of 4.77 kWh/m²/day and approximately 27,500 tons of biomass residues annually, the proposed 40 MW solar PV, 25 MW biomass, 100 MWh battery storage, and 10 MW grid backup system was found to be technically feasible. The system can generate about 157,760 MWh annually, achieve an 87.3% renewable energy fraction, and provide a reliable electricity supply. Economically, the system is also viable, with an NPC of ₦780 million and LCOE of ₦92.5/kWh, making it a cost-effective alternative to diesel-based generation. It is further expected to reduce major emissions by more than 79%, lower household energy costs, improve electricity access, create employment, and support local economic development. The 86% public acceptance rate further demonstrates its social viability and potential contribution to Nigeria's renewable energy transition and energy security.

Recommendations included:

- i. Mechanical engineers should apply advanced modelling and optimization tools to improve system sizing, energy balance, and overall efficiency.
- ii. Locally adaptable biomass gasification and conversion technologies should be developed to maximize the use of the estimated 27,500 tons of biomass residues and support employment.
- iii. Improved combustion, heat recovery, turbine, and generator designs should be adopted to enhance thermal efficiency and reduce operating costs and emissions.
- iv. Preventive maintenance frameworks and monitoring technologies should be established to address maintenance concerns and ensure long-term system reliability.
- v. Advanced battery management and cooling systems should be incorporated to maintain the performance and reliability of the 100 MWh storage system under Omoku's tropical conditions.

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