

Techno-Economic Sustainability Analysis of Optimal Microgrid Systems with Hybrid Renewable Energy Technologies

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Abstract- The increasing global demand for clean, reliable, and economically viable electricity has accelerated the adoption of micro-grid systems integrating multiple renewable energy technologies. Hybrid renewable micro-grids combining resources such as solar PV, wind, biomass, and energy storage offer significant potential for enhancing energy resilience while reducing dependence on fossil fuels. However, determining the optimal configuration of these systems requires comprehensive evaluation of their technical performance, economic feasibility, and long-term sustainability. This study presents a techno-economic sustainability analysis of optimal micro-grid systems incorporating hybrid renewable energy technologies. Using advanced optimization techniques, the research assesses system configurations under varying load demands and resource conditions to achieve an optimal balance between cost, reliability, and environmental performance. Key indicators such as Levelized Cost of Energy (LCOE), Net Present Cost (NPC), renewable fraction, system reliability index, and carbon emission reduction potential are analyzed to quantify the system's performance. The findings demonstrate that properly optimized hybrid renewable micro-grids can significantly reduce lifecycle costs and emissions while ensuring a stable power supply, making them a viable solution for rural electrification, grid support, and sustainable energy transitions. This work provides critical insights for policymakers, system designers, and energy planners seeking to implement resilient, low-carbon micro-grid systems for enhanced energy sustainability.

Keywords - Hybrid renewable energy systems, Levelized Cost of Energy (LCOE), Microgrid optimization, Net Present Cost (NPC), Optimization modelling, Techno-economic analysis.

I. INTRODUCTION

Renewable energy technologies have become increasingly vital due to their environmental sustainability, falling costs, and adaptability across different scales. Solar and wind energy are now among the cheapest sources of electricity, with levelized costs dropping to \$0.03–\$0.05/kWh, making them more economical than new fossil fuel power plants. Their modular nature and short installation periods make them suitable for both rural off-grid applications and large utility-scale systems. By relying on abundant natural resources such as sunlight and wind, these technologies reduce environmental impact, support climate goals, and lower dependence on fossil fuels. Additionally,

their affordability and scalability help expand access to clean and reliable electricity, promoting energy equity and supporting global sustainable development (Ijeoma, 2025).

Uche-Ibe, Amadi, and Ijeoma. (2026) studied the Multi-Objective Optimisation of Micro-grid Design with Hybrid Renewable Energy Sources for a Sustainable Environment, successfully demonstrating the potential of hybrid energy systems to provide reliable, cost-effective, and eco-friendly electricity. By integrating solar, wind, battery storage, and optional diesel generation, the research established a balanced framework that addresses the conflicting objectives of minimizing cost, reducing emissions, and ensuring system reliability. Over time, non-renewable energy sources have negatively impacted both humanity and the

environment. Renewable energy sources, on the other hand, have been recognised for their significant potential to supply far more energy than the world currently requires. Sustainable energy can be derived from accessible and indigenous resources, such as wind, biomass, hydropower, geothermal, and solar energy (Herzog et al. 2001). As renewable energy technologies become more cost-effective and oil and gas prices remain unpredictable, the transition to renewable energy systems is becoming increasingly viable. In recent decades, the adoption of solar and wind power systems has surged, driven by decreasing capital costs and electricity generation prices, alongside advancements in efficiency (Strielkowski et al. 2021). Furthermore, while fossil fuel prices and their associated social and environmental costs continue to rise, renewable energy costs are steadily declining (Chel and Kaushik, 2018).

A DC microgrid is a network comprising DC power components, such as a DC voltage/current source and its accompanying circuitry. In this work, a DC grid comprises six solar PV arrays, with each array consisting of 32 12V panels arranged in an 8x4 configuration (8 columns, 4 rows). Thus, each PV array has a total voltage of 72V. These PV arrays are connected to individual contactors (MCB1-6). This DC grid was capable of fault detection through the use of smart electronics comprising an Arduino Nano microcontroller, a WCS1600 current sensor, and an LCD. Fault detection and localization were accomplished by integrating a Simatic S7-1200 CPU 1214C PLC into the system, with a sensing range of 200A (Amadi et al., 2025)

Many studies have explored the unreliability of electrical energy supply to consumers and proposed both technical and economic solutions. A review of recent studies reveals that numerous hybrid renewable energy systems (HRES) have been analyzed using the Hybrid Optimization of Multiple Energy Resources (HOMER) software (Sen and Bhattacharyya, 2014). While much of the focus has been on addressing rural electrification challenges through standalone systems, these efforts have provided valuable insights into the optimal design and planning of hybrid systems. However, there is a

pressing need for detailed research on the planning and design of microgrid systems for urban settings. This research should emphasize the integration of diverse renewable energy sources, energy storage systems, and smart grid technologies to ensure a stable and efficient energy supply.

Abnavi et al. (2019) evaluated the techno-economic feasibility of an off-grid hybrid power system for a rural area in the Bushehr province of Iran using HOMER. Their study analyzed the net present cost, cost of energy (COE), and renewable fraction of various hybrid configurations. The optimal configuration was a wind/PV/diesel/battery system, achieving a 61.4% renewable energy fraction and reducing fuel consumption and carbon dioxide emissions by 664 tons. Sensitivity analysis showed that increasing fuel prices would make a wind/PV/battery system more economical, achieving 100% renewable energy penetration if fuel prices exceeded \$0.5/L. However, the study did not explore long-term sustainability, scalability, policy impacts, social acceptance, detailed cost structures, or the potential for future grid integration. Electrical power systems are designed to provide consistent and reliable voltage to end users (Amadi et al., 2025). The demand for electrical power is rapidly increasing in emerging economies, leading to more complex power system networks (Okosi, Amadi, and Ijeoma, 2025).

To address these intermittencies, various technologies are deployed. The seamless integration of renewable energy sources with the utility grid is a critical aspect of future energy systems, offering numerous benefits, including voltage support, load shifting, grid stability, and system resilience. Despite these advantages, power management remains a significant challenge in renewable power generation. The study employed an advanced optimization and energy management strategy based on a fuzzy logic algorithm to ensure the efficient operation of the hybrid system and achieve the desired outcomes (Amadi et al., 2025).

Odou et al. (2019) analyzed the techno-economic feasibility of an HRES for rural electrification in Fouay village, Benin, using HOMER software for

optimization, simulation, and sensitivity analysis. Their study identified a solar PV/diesel generator (DG)/battery system as the most cost-effective configuration, reducing battery requirements by 70% compared to a PV/battery system and achieving a 97% reduction in CO₂ emissions compared to a conventional DG system. The paper emphasised the importance of considering local energy resource availability and the distance of the power plant when designing HRES. Despite the study's strengths, it did not examine the system's adaptability to long-term changes in energy demand or its ability to integrate with future grid expansions.

Arefin et al. (2022) designed and optimized off-grid HRES for two locations in Dhaka and Khulna, Bangladesh, using solar PV, wind turbines, battery storage, and diesel generators. They analyzed five load dispatch strategies: Combined Dispatch, Load Following, Generator Order, HOMER Predictive Strategy, and Cycle Charging. HOMER Pro was used for techno-economic analysis, while MATLAB/Simulink modelled the system's power response. Their findings concluded that Load Following dispatch minimized levelized energy costs, CO₂ emissions, and net present costs, while Combined Dispatch performed the worst. However, the study failed to account for the stochastic nature of wind and solar resources and overlooked load transfer considerations based on real-time power flow.

Alhawsawi et al. (2023) focused on the planning and design of HRES for microgrid applications at Oakland University, integrating solar PV, energy storage systems, combined heat and power (CHP), and wind turbines using HOMER Pro software. Their study emphasized the reduction of unmet loads to ensure a reliable energy supply while promoting scalability and flexibility for future expansions. The microgrid configurations reduced reliance on traditional grid sources and significantly cut greenhouse gas emissions, with a net present cost (NPC) of USD 30 million and a levelized cost of energy (LCOE) of USD 0.00274/kWh. However, some load remained unmet during specific periods, revealing the need for further refinement.

The cited literature provides substantial solutions using HOMER Pro software, showcasing various dispatch strategies and configurations tailored to the specific resources and conditions of the studied areas. However, several studies [(Agajie, et al., 2023), (Abnavi, et al., 2019), (Sharma et al., 2022), (Rajanna and Saini, 2016)] fail to incorporate provisions for grid-connected systems, focusing instead on standalone configurations or generic rural area load profiles. These studies primarily analyze energy solutions for rural areas without delving into the complexities of integrating hybrid renewable energy systems (HRES) into grid-connected environments.

Heyam, et al. (2022), however, stands out by addressing this limitation. Their grid-tied design demonstrates the potential for incorporating HRES into a larger utility framework, bridging the gap between standalone and grid-connected systems. Despite this progress, their study exhibits a notable shortcoming in the techno-economic analysis: the simulation does not fully incorporate grid utility data, which limits its applicability for holistic grid integration assessments.

Although Rajanna and Saini (2016) introduced demand-side optimization to improve system performance, their configuration still relies on a generic rural area load and does not extend to grid-tied solutions. This limitation emphasises the need for a more comprehensive analysis that considers specific load dynamics and grid interactions. These observations underscore significant gaps in the existing literature; addressing it is critical for advancing the field and ensuring that hybrid systems can meet the evolving energy demands of urbanized regions.

Renewable Energy Sources

Renewable energy refers to energy derived from natural sources that can be replenished quickly after use. Often described as clean or alternative energy, it is contrasted with conventional energy generation methods. Examples of renewable energy sources include solar, wind, water, biomass, and geothermal energy (Lawson, 2019). These sources exist in various forms and employ different conversion technologies

to generate usable energy products such as heat, electricity, and liquid fuels.

With immense potential, renewable energy sources could theoretically meet and exceed global energy demands. Sources like wind, biomass, hydropower, geothermal, and solar energy provide sustainable energy services by leveraging readily available and indigenous resources. Oil and gas prices continue to fluctuate as their costs decline, and the likelihood of switching to renewable energy systems is growing. Over the last few decades, there has been a rapid expansion in the sales of solar and wind power systems, together with a fall in their capital costs and energy generating rates. Additionally, these systems have continued to improve in performance (Strielkowski et al. 2021). Renewable energy sources have a lot of potential and could theoretically provide a lot more energy than the world needs. Renewable energy sources such as wind, biomass, hydropower, geothermal, and solar power can provide sustainable energy services by utilizing easily accessible, native resources.

Prices for oil and gas are still volatile despite falling costs, and there is an increasing chance that we will move to renewable energy sources. Sales of solar and wind power systems have increased dramatically during the past few decades, coinciding with a decline in both capital costs and rates of energy generation. Furthermore, the performance of these systems has kept getting better, increasing the likelihood that they will be used as primary energy producing sources (Chel and Kaushik, 2018). To be objective, though, one must address the limitations of renewable energy sources, such as wind and solar power. The primary issue with renewable energy is its sporadic nature. Energy storage devices must be used alongside these energy sources to achieve a peak shaving function in order to resolve this problem. Therefore, the electricity produced from a variety of renewable energy sources may create gaps in time and space between the energy's availability and end consumers' usage of it (Setyowati, 2021).

According to a United Nations report, hydroelectric power plants account for over half of the electricity generation capacity in developing countries across

Southeast Asia. In countries like India, renewable and decentralized energy systems are increasingly competing with fossil fuel-based electricity generation. This shift creates opportunities to make renewable energy more affordable, reliable, and efficient. A recent IEA study commended the Indian government for its initiatives to improve access to electricity and clean cooking solutions for its citizens. The report also highlighted India's progress in adopting market-based approaches to address energy security challenges, advancing renewable energy development, improving energy efficiency, and ensuring access to clean and affordable energy. These achievements demonstrate that the potential of renewable energy sources significantly outweighs their current limitations. Examples of renewable energy sources are discussed below.

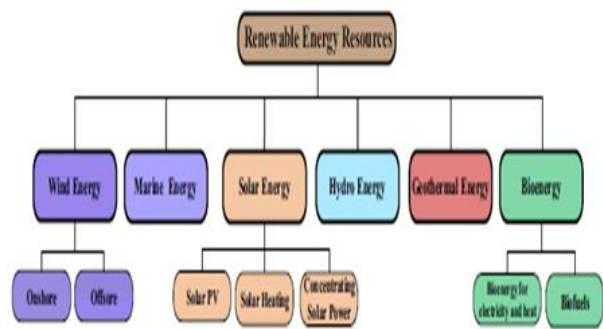


Figure 1: Overview of Renewable Energy

Wind Energy

Wind, as commonly known, is the kinetic energy generated by air in motion. It has been harnessed for centuries, dating back to around 635 AD, primarily for water pumping and grain milling. Wind results from air movement across the Earth's surface, driven by differences in high and low atmospheric pressure (Renewable Energy UK, 2021). Essentially, wind energy is a by-product of solar energy. The sun radiates approximately 170,000,000 GW of energy onto the Earth's uneven atmosphere and irregular surfaces. This energy is absorbed by the ground, surfaces, and surrounding air, creating temperature variations. These temperature differences, combined with the Earth's revolution around the sun, generate wind.

Globally, the average wind kinetic energy was approximately 1.50 MJ/m² between 1979 and 2010,

with 1.31 MJ/m² in the Northern Hemisphere and 1.70 MJ/m² in the Southern Hemisphere. The atmosphere functions as a thermal engine, absorbing heat at higher temperatures and releasing it at lower temperatures, driving the production of wind kinetic energy at a rate of 2.46 W/m², which sustains atmospheric circulation against friction. Wind energy is abundant, with its supply far exceeding current demand. Notably, the total amount of economically extractable wind power is significantly greater than the present energy consumption from all sources, making wind energy inexhaustible as long as sunlight reaches the Earth (Huang and McElroy, 2015).

Biomass Energy

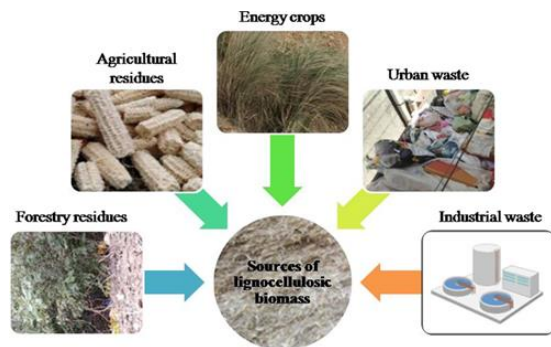


Figure 2: Types of Bio-fuels from Biomass (Source: Clauser et al., 2021)

Bio-energy, derived from biomass, is a versatile and widely available renewable energy source produced from various organic materials such as wood and wood processing waste, agricultural crops and residues, biogenic components in municipal solid waste, animal manure, and human sewage. Biomass accounts for approximately 14% of the world's final energy consumption, ranking fourth among energy sources globally higher than coal (12%) and comparable to gas (15%) and electricity (14%) (Sarkodie and Owusu. 2016). Among biomass sources, corn and soy are the most commonly utilized for energy production (Pehlken et al. 2020). The use of biomass as an energy source dates back over a million years, starting with wood combustion for fire, which marked a transformative phase in human civilization (Strezov and Evans, 2024). Combusting biomass to generate electricity remains

one of the simplest ways to produce bio-energy. The lignin content in plant biomass serves as a high-energy resource, enabling the conversion of biomass carbohydrates into biofuels, bio-chemicals, cellulose-based ethanol, bio-based adhesives, biomaterials, and electricity. The relative value of electricity versus liquid fuels often determines the optimal utilization of biomass.

Biomass is typically measured in terms of mass per unit area (e.g., g/m² or Mg/ha) as dry weight, excluding water content unless specified otherwise. It usually encompasses only living materials. Importantly, biomass is the only renewable resource currently capable of producing high-energy-density liquid fuels (Song, 2012).

Bioenergy offers considerable potential for reducing greenhouse gas emissions when developed sustainably and implemented through efficient systems. Current technologies, alongside future innovations such as perennial cropping systems, utilization of biomass residues and waste, and advanced conversion methods, can achieve emission reductions of 80–90% compared to traditional fossil fuels (Song, 2012). Biomass can be converted into energy through several processes, including:

- Direct Combustion: Burning biomass to generate heat.
- Thermo-chemical Conversion: Transforming biomass into solid, liquid, or gaseous fuels through processes like pyrolysis or gasification.
- Chemical Conversion: Producing liquid fuels, such as biodiesel, through chemical reactions.
- Biological Conversion: Using microorganisms to create fuels like ethanol or biogas through fermentation or anaerobic digestion.
- In addition to traditional bio-fuels like ethanol and biodiesel, biomass can also yield hydrocarbons and other chemical products typically derived from fossil fuels. These bio-fuels are suitable not only for vehicles but also for aviation and maritime applications. Furthermore, modern bio-refineries enhance the economic viability of biomass by enabling the production of a wide range of bio-based products, making bio-energy a critical player in

transitioning to cleaner energy systems (Song, 2012).

Hydro Energy

Hydropower, one of humanity's earliest energy sources, derives its name from the Greek word ὕδρω, meaning water. It harnesses the movement of water to generate energy, which can power machinery or produce electricity. Hydroelectric power specifically refers to the production of electricity from hydropower, typically achieved by altering the natural flow of a river or water body using a dam or diversion structure. Hydropower is a renewable energy source that accounts for approximately 70% of global renewable energy production. Other renewable energy sources include geothermal, wave, tidal, wind, and solar energy. Unlike conventional power plants, which often cause environmental pollution, hydroelectric plants do not consume resources during electricity generation.

Hydropower has played a pivotal role in advancing the electric power sector. Both small and large hydroelectric power plants have contributed significantly to the early and ongoing development of the industry. This form of energy relies on water in motion, often referred to as "water at work". Hydropower is indirectly a form of solar energy, as the sun drives the hydrologic cycle. This cycle brings atmospheric water to the Earth's surface through precipitation, which then infiltrates the soil, forms surface runoff, or evaporates. Water from rainfall and snowmelt eventually accumulates in ponds, lakes, reservoirs, or oceans, where evaporation continually occurs.

For many developed and developing nations, hydroelectric power remains a cornerstone of socioeconomic development. With modern technology and a growing global population, the demand for energy has surged, particularly for electricity generation, water pumping, construction, and transportation. Energy, while it cannot be created or destroyed, is transformed from one form to another during electricity production. Flowing water provides the kinetic energy necessary for power generation. As water turns the blades of a turbine, this kinetic energy is converted into

mechanical energy. The turbine's motion then powers a generator, transforming the mechanical energy into electrical energy. This process results in hydroelectric power, often called hydropower, because water serves as its energy source.

Hydropower is generated in facilities known as hydroelectric power plants. While some plants are built along rivers, streams, or canals, dams are often essential to ensure a reliable water supply. Dams store water for later use in electricity generation, irrigation, and domestic or industrial applications. The reservoir created by a dam functions like a battery, holding water in reserve for controlled release when electricity demand arises (Chel and Kaushik, 2018).

Geothermal Energy

Geothermal energy has been in use by humans since the Paleolithic era, with hot springs serving as natural baths during the Stone Age. The ancient Romans later utilized geothermal energy for space heating. The term "geothermal" is derived from the Greek words γη (geo), meaning earth, and θερμός (thermos), meaning hot. It refers to heat energy stored beneath the Earth's surface (Askari et al. 2015). This energy originates from both the planet's formation and the decay of radioactive materials.

The temperature difference between the Earth's core and its surface drives a steady flow of thermal energy from the interior to the exterior. Scientists have determined that the Earth's inner core has an estimated temperature of about 10,800°F, making it as hot as the sun's surface! This immense heat, combined with high pressure, causes some rocks to melt and parts of the solid mantle to behave plastically. Temperatures within the mantle range from approximately 392°F near the crust-mantle boundary to about 7,230°F at the mantle-core boundary (U.S. Energy Information, 2022).

This geothermal heat is absorbed by rocks and water beneath the Earth's surface, with deeper layers retaining higher temperatures. The amount of usable geothermal energy depends on the depth of the heat source and the method of extraction. Over time, geothermal energy has been harnessed for various

applications, including cooking, bathing, space heating, electricity generation, and other purposes.

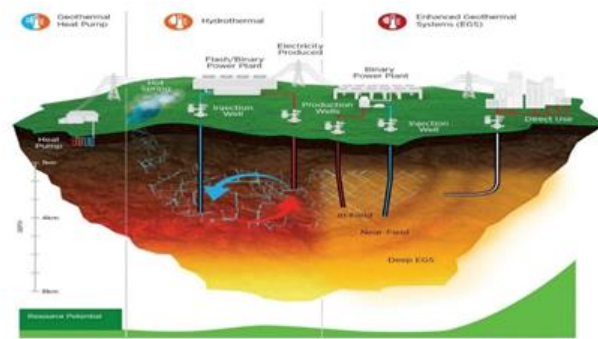


Figure 3: Geothermal Energy (Source: El-Leil et. al., 2024)

Solar Energy

Solar energy, the most abundant of all energy sources, refers to radiation from the sun that can be transformed into either thermal energy (heat) or electrical energy. It holds vast potential, with the National Renewable Energy Laboratory noting that “more energy from the sun strikes the Earth in one hour than is consumed globally in an entire year” (National Renewable Energy Laboratory, 2020). To put this in perspective, the energy intercepted by Earth from the sun is about 10,000 times greater than the total energy consumption of humanity. Remarkably, solar energy can still be harnessed even on cloudy days, offering the potential to meet current and future global energy demands. Solar technologies provide diverse solutions, including heating, cooling, natural lighting, electricity generation, and fuel production. This energy conversion is achieved either through photovoltaic (PV) panels or mirrors that focus solar radiation. One of the primary advantages of solar energy is its inexhaustible and environmentally friendly nature, making it a sustainable alternative to conventional energy sources.

Solar technologies also provide significant benefits to businesses and industries by reducing costs, increasing efficiency, and diversifying energy sources. On a larger scale, utilities and energy producers use photovoltaic systems and concentrated solar power technologies to generate electricity for urban and rural communities.

Table 1: Solar Radiation and Sunlight Daily Duration for Coastal and Inland Region

Month	Warri Solar Radiation (MJ/m ² /day)	Warri Sunlight Daily Duration (h)	Enugu Solar Radiation (MJ/m ² /day)	Enugu Sunlight Daily Duration (h)	Abuja Solar Radiation (MJ/m ² /day)	Abuja Sunlight Daily Duration (h)	Kano Solar Radiation (MJ/m ² /day)	Kano Sunlight Daily Duration (h)	Maiduguri Solar Radiation (MJ/m ² /day)	Maiduguri Sunlight Daily Duration (h)
Jan	19.61	5.4	19.9	6.3	20.8	8	20.3	8.5	20.32	9.2
Feb	19.9	5.5	20.4	6.4	21.6	8.3	22.6	8.8	22.9	9.4
Mar	18.58	4.9	20	5.9	21.7	7.4	23.7	8.2	24.5	8.9
Apr	17.59	5.4	19	6.1	20.7	7.2	23.6	8.3	24.64	8.5
May	16.26	5.3	17.7	6	19.3	7.3	22.6	9	23.71	9.1
Jun	14.14	4.2	15.9	5.1	17.7	6.6	21.6	9.2	22.82	8.9
Jul	12.54	3.2	14.2	3.7	16.1	5.2	19.4	7.8	20.54	7.5
Aug	12.84	2.9	13.8	3.6	15.1	4.8	18.2	7.5	19.2	7.1
Sep	13.23	3.3	14.7	4	16.4	6	19.9	8.4	20.66	8
Oct	14.64	4.5	16.5	5.6	18.3	7.9	21	9.2	21.22	9.8
Nov	16.88	6	18.5	7.4	20.4	9.3	21	9.4	20.56	10.1
Dec	18.7	6	19.4	7.3	20.6	9.2	19.8	9.6	20.44	11

II. MATERIALS AND METHOD

The proposed micro-grid system integrates wind turbine, solar photovoltaic generator, battery storage and grid connection to ensure a reliable, efficient and sustainable power supply. The system utilizes a fuzzy logic controller (FLC) to manage and optimize the energy flow between these components, addressing the variability and uncertainty inherent in renewable energy sources. The operational scenario of the system is such that during high renewable generation, excess energy from wind turbine and solar photovoltaic generator is used to charge the battery and export surplus energy to the grid. Similarly, during low renewable generation, the battery storage discharges to meet load demand and additional power is imported from the grid if necessary. At moderate renewable generation, the system balanced the charging and discharging of the battery to match load demand while minimizing grid interaction.

Wind Turbine System Modeling

Wind turbine is a device that converts the kinetic energy of wind into electrical energy. When wind blows, the main shaft in the drive train starts to rotate. The gearbox increases the speed level of the turbine to a level suitable to drive the generator. For higher efficiency, the speed of the turbine varies with the wind velocity hence the use of variable speed generator system is the most popular trend in wind turbine energy conversion system.

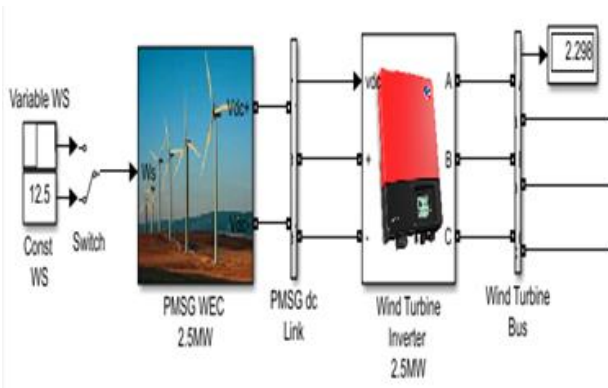


Figure 4: Wind turbine Modelling

Kinetic Energy of Wind in Air

The kinetic energy of the wind is given by;

$$E = \frac{1}{2} m V_w^2 \quad (1)$$

Where;

m: mass of air

V_w : wind velocity

Mass Flow Rate of Wind in Air

The mass flow rate of wind in air given by

$$\frac{dm}{dt} = \rho A V_w \quad (2)$$

Where;

ρ : density of air

A: area through the wind

V_w : wind velocity

Wind Power Received by the Wind Turbine

The wind power received by the turbine is equal to the rate of change of kinetic energy given by

$$P_{av} = \frac{d}{dt} (E) \quad (3)$$

$$P_{av} = \frac{1}{2} \frac{dm}{dt} V_w^2 \quad (4)$$

Substituting (2) into (4)

$$P_{av} = \frac{1}{2} \rho A V_w^3 \quad (5)$$

Where;

m: mass of air

A: area swept by the wind turbine

V_w : wind speed

ρ : density of air

Shaft Power of the Wind Turbine

The power converted into mechanical energy is given by:

$$P_{mech} = \frac{1}{2} C_p \rho A V_w^3 \quad (6)$$

Where;

m: mass of air

A: area swept by the wind turbine

V_w : wind speed

C_p : power coefficient of wind turbine

ρ : density of air

Power Coefficient of a Wind Turbine

The wind turbine power coefficient serves as a metric for evaluating the conversion efficiency of a wind turbine. It is defined as the ratio of the mechanical power generated to the total power captured by the wind turbine. A single 2.5MW wind turbine installed at a well-suited site with average wind speeds above 6.0 m/s can produce around 6.57 GWh of energy per year.

Mathematically, it is expressed as;

$$C_p = \frac{P_m}{P_{av}} \quad (7)$$

Where;

P_m : is the mechanical power output of the turbine.

Sizing of the Wind Turbine

Target Output: 2.5 MW

Required Average Wind Speed: ≥ 6.0 m/s at hub height (80–100 m)

Turbine Configuration: 1 \times 2.5 MW (preferred), or 2 \times 1.25 MW

Rotor Diameter: ~ 110 – 125 m

Hub Height: ~ 80 – 100 m

Cut-in/Cut-out Speeds: ~ 3 – 4 m/s / ~ 25 m/s

Capacity Factor: 30% (at good wind site)

Annual Output: 2.5 MW \times 8,760 hrs. \times 0.30 = 6.57 GWh/year.

Shaft Power of the Wind Turbine

The power converted into mechanical energy is given by:

$$P_{mech} = \frac{1}{2} C_p \rho A V_w^3 \quad (8)$$

Where;

m: mass of air

A: area swept by the wind turbine

V_w : wind speed

C_p : power coefficient of wind turbine

ρ : density of air

Hence, theoretical Power Equation: $P = 0.5 \times \rho \times A \times V^3 \times C_p$

Given;

Air Density (ρ): 1.225 kg/m³

Power Coefficient (C_p): 0.4

Rotor Diameter: 100 m (Radius = 50 m)

Wind Speed: 6 m/s

Swept Area (A): $\pi \times 50^2 = 7,854$ m²

Power Output ≈ 2.5 MW

Electrical Infrastructure;

Generator Type: Gearless or geared induction/synchronous
Turbine Output Voltage: ~690 V
Step-up Transformer: 690 V to 11–33 kV
SCADA System: For real-time monitoring
Grid Compliance: Protection, metering, and synchronization.

Techno-Economic Analysis using Homer Pro.

Techno economics is a crucial aspect of the HRES design. The focus is to minimize the Net Present Cost (NPC), which is the difference between the present values of all costs, incurred and the present value of all the lifetime revenue earn. The NPC and Cost of Electricity (COE) are used to choose the most techno-economic viable Hybrid Renewable Energy System as they enable a designer determine the optimal configuration and operating the system in term of the economics.

Net Present Cost

$$NPC = \left(CC + \sum_{i=1}^N \frac{(RC+O\&MC+FC-SV)}{(1+i)^N} \right) \tag{9}$$

Where;

- CC: Capital cost
- RC: Replacement Cost
- O&MC: Operating and maintenance cost
- FC: Fuel Cost
- SV: Salvage Cost
- i: Interest rate
- N: Number of years (Project life time).

Cost of Electricity

$$COE = \frac{C_{ann,tot} - C_{boiler} * H_{served}}{E_{served}} \tag{10}$$

Where;

- C_{ann,tot}: total annualized cost of the system
- C_{boiler}: boiler marginal cost
- H_{served}: total thermal load served
- E_{served}: total electrical load served

Results and Discussion

Figure 5 shows the plot of Total power generation (MW) against Time (T=24hours) in maximum power extraction from solar and wind energy under varying temperature and irradiance (See Appendix A for meteorological data of Jetty Area of Abuloma Community Obtain from NASA data Power Viewer) and shows there was significant improvement in terms of power extraction, as the maximum power extracted from the PV array and wind turbine are 6MW and 2MW respectively despite fluctuations in irradiance and other external conditions.

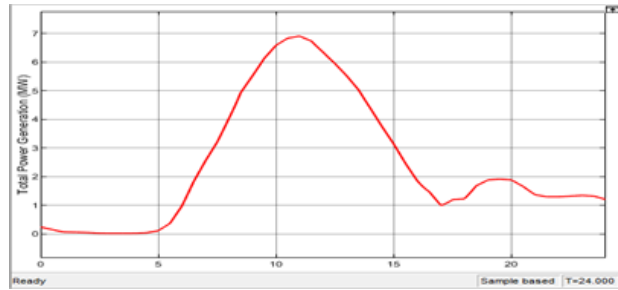


Figure 5: Plot of Total Power Generation from Hybrid Renewable Energy Sources

Figure 6 illustrates the configuration of the hybrid renewable energy system used for techno-economic analysis within the HOMER software environment. This setup aims to determine the most feasible configuration capable of efficiently meeting the load demand. The optimization process involves simulating all potential solutions for the hybrid renewable energy system configuration. HOMER then organizes the various feasible combinations based on the Total Net Present Cost (TNPC), displaying them in ascending order, with the option featuring the lowest TNPC appearing at the top of the list. Additionally, sensitivity analysis options are available in the upper section of the interface to explore the impact of key variables on system performance.

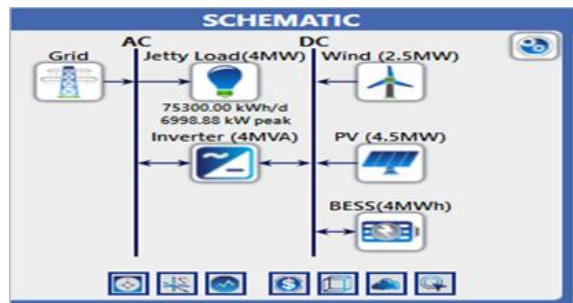


Figure 6: Hybrid Renewable Energy System Configuration in HOMER Software Environment

Figure 7 shows the sensitivity and optimization result simulated in HOMER to obtain the best feasible configuration of the designed system which can efficiently serve the load demand. The optimization process is done after simulating the complete possible solution of the DHRES configuration. The elimination of infeasible combinations is the essence of the sensitivity analysis; it also enables the ranking of the feasible combinations considering the input

parameters uncertainty or risk. HOMER displays the various combinations possible based on the Net Present Cost (NPC) in ascending order, leaving the lowest at the top of the list, and the options of sensitivity at the upper part of the screen. For each sensitivity value, there is a corresponding optimization values. One of the key features of HOMER is its ability to take into account future change or fluctuations, like changes in load demand, fluctuations of renewable resources.

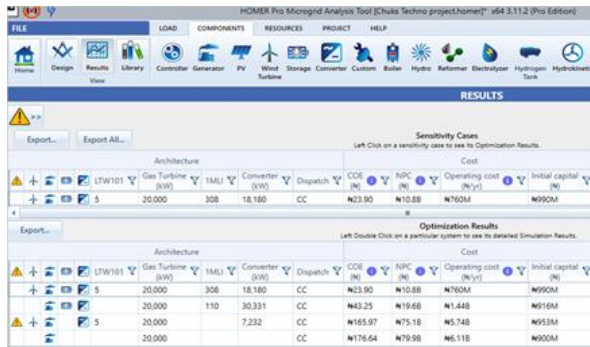


Figure 7: Sensitivity and Optimization Result

Table 2 presents the results of the techno-economic analysis performed using HOMER software to evaluate and compare the cost-effectiveness of energy system configurations for Jetty distribution network. The analysis is aimed at determining the optimal system configuration by minimizing the Net Present Cost (NPC), which encompasses all present and future costs while considering revenues generated over the system’s lifetime and ensures an economically sustainable and efficient energy system. The cost metrics are for this configuration is: Initial Cost: ₦990,251,352.19, Replacement Cost: ₦414,669,375.12, Net Present Cost (NPC): ₦10,813,540,000.00, Operating Cost: ₦759,874.00, Levelized Cost of Electricity (COE): ₦230.90/kWh, Operation and Maintenance (O&M) Cost: ₦9,371,226,274.97, Salvage Value: -₦37,522,385.49. This improvement is primarily attributed to the low O&M and no fuel costs associated with renewable energy resources which reduce the burden on the grid, thereby extending its operational life and reducing the frequency of replacements.

Table 2: Compared Techno--Economic Analysis

S/N	Type	Amount
1	Capital Cost	₦990,251,352.19
2	Replacement Cost	₦414,669,375.12
3	Net present cost (NPC)	₦10,813,540,000.00
4	Operating Cost	₦759,874,
5	Cost of Electricity (COE)	₦230.90
6	O&M Cost	₦9,371,226,274.97
7	Salvage	-₦37,522,385.49

Table 3 presents the greenhouse gas (GHG) emission analysis in HOMER software to provide critical insights into the environmental impact and emissions savings associated with renewable energy integration. The corresponding greenhouse gas emissions for the hybrid system are as follows: 15,194,957 kg/year of Carbon Dioxide (CO₂), representing a significant reduction, 78,611 kg/year of Carbon Monoxide (CO), showcasing a drastic decrease in harmful pollutants, 4,172 kg/year of Unburnt Hydrocarbons (UHC), reducing photochemical smog formation., 672 kg/year of Particulate Matter (PM), improving air quality, 37,143 kg/year of Sulphur-Dioxide (SO₂), contributing less to acid rain, 15,066 kg/year of Nitrogen Oxides (NO_x), minimizing smog and acidification potential. The total emissions for the hybrid system amount to 15,330,621 kg/year. The integration of solar and wind energy into the power generation system results in significant environmental benefits. The enhanced air quality and reduced health risks associated with particulate matter, carbon monoxide, and other pollutants which a marked decrease in the ecological footprint of energy generation, aligning with global sustainability and de-carbonization goals.

Table 3: Compared GHG Emission

Type	Value

Carbon Dioxide (CO ₂)	15,194,957 kg per year
Carbon Monoxide (CO)	78,611 kg per year
Unburned Hydrocarbons (UHC)	4,172 kg per year
Particulate Matter	672 kg per year
Sulfur Dioxide (SO ₂)	37,143 kg per year
Nitrogen Oxides (NO _x)	15,066 kg per year

The study successfully developed a fuzzy logic-based Battery Management System (BMS) that maintains the battery's State of Charge within the optimal 20–80% range, enhancing both reliability and lifespan. It also implemented a grid supervisory control algorithm that enables smooth synchronization with the main grid and supports peak demand management, especially when renewable generation is low and battery charge is insufficient. Overall, the research offers practical guidance for the Port Harcourt Electricity Distribution Company (PHEDC), emphasizing the benefits of adopting additional renewable energy sources such as solar and winds to improve energy availability and management efficiency.

III. CONCLUSION

This study examined the techno-economic sustainability of optimal micro-grid systems integrating hybrid renewable energy technologies, highlighting their potential to deliver reliable, affordable, and environmentally responsible electricity. The analysis demonstrates that optimal configurations tailored to local resource availability, load profiles, and economic constraints can significantly reduce lifecycle costs, enhance system reliability, and improve renewable energy penetration. Metrics such as LCOE, NPC, renewable fraction, and emission reduction potential confirm that hybrid micro-grids outperform single-source or diesel-dependent systems across key performance dimensions. The findings underscore that hybrid renewable micro-grids represent a practical and scalable pathway toward achieving energy security

and sustainable development, particularly in remote and underserved communities. Their techno-economic advantages make them well-suited for rural electrification, grid stabilization, and the broader transition toward low-carbon energy systems. Nonetheless, successful deployment requires informed planning, supportive policy frameworks, and investment mechanisms that recognize the long-term benefits of decentralized renewable generation. Future research should explore advanced control strategies, real-time optimization, and the integration of emerging technologies such as hydrogen storage and AI-based forecasting to further enhance micro-grid performance.

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