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Optimal Sizing of Hybrid Micro-Grid System for Rural Communities in Kaduna State Using Improved Grey Wolf Algorithm

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ABSTRACT

The growing interest in microgrid design, operation, and optimization has led to a significant focus on optimal sizing of microgrid components. A microgrid is a localized, small-scale power system that integrates different energy sources (renewable and/or conventional), energy storage, and loads within a defined area. It can operate in grid-connected mode or islanded(off-grid) mode. The primary goals of microgrid optimal sizing include enhancing energy efficiency, system reliability, cost-effectiveness, and sustainability. To address this, researchers have developed an improved grey wolf optimization algorithm (IGWOA) for optimal sizing of off-grid hybrid microgrid systems consisting of photovoltaic (PV), wind turbine (WT), and battery energy storage (BES). This research utilized atmospheric weather data from the Nigerian Meteorological Agency and load demand data from the Kaduna electricity distribution center to demonstrate the effectiveness of the proposed approach. The microgrid optimal sizing problem was formulated as a constrained single objective optimization problem, considering constraints such as loss of power supply probability (LPSP), power balance, generation limits, and battery state of charge (SOC) limits. Three scenarios were considered in this research. Firstly, the target allowable maximum LPSP was fixed at 25% and the optimal sizing of the hybrid microgrid components and minimizing of the cost to #112,356.4 means #170,159,791.32) per year was obtained by the algorithm. Secondly, the impact of the target allowable maximum LPSP variation was again examined, and it was discovered increase in LPSP decreases the total installed capacity of the distributed energy resources (DERs), hence minimizing the total cost. Hence, the individual installed capacities of PV, WT, and BES varies arbitrarily with increase in LPSP. Furthermore, Lastly, in order to validate the proposed strategy, a comparative analysis between the IGWOA and other four algorithms viz, Particle Swarm Optimizer (PSO); Differential Evolution (DE); Water Cycle Algorithm (WCA); and the conventional Grey Wolf Optimizer (GWO) was carried out, and the result showed the applicability of the proposed algorithm. The study provides a long-lasting solution for optimal sizing of PV, WT, and BESS hybrid microgrid design, with simulations conducted in the MATLAB Software environment.

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INTRODUCTION

Traditional power generation primarily relies on fossil fuels, which are the leading contributors to greenhouse gas (GHG) emissions and global warming. As electricity demand continues to rise, so does the dependence on fossil fuels, resulting in a proportional increase in GHG emissions. Currently, the world faces both a rapid depletion of fossil fuel resources and the adverse effects of climate change driven by these emissions [1]. There is now a broad global consensus that greenhouse gases such as carbon dioxide, methane, sulfur hexafluoride, and hydrofluorocarbons pose a serious threat to the environment.

Unchecked increases in these emissions could lead to catastrophic rises in global temperatures, endangering ecosystems and human life [2]. This growing concern has prompted a global push to reduce GHG emissions, particularly those from electricity generation using coal, oil, and natural gas. As a result, new environmental regulations are being introduced. For example, over 160 countries have signed the Paris Agreement to combat climate change [3]. In line with this commitment, many nations are setting ambitious targets to cut emissions for instance, Saudi Arabia aims to reduce CO_2 emissions by 130 million tons annually by 2030 [4]. Given these challenges, there is an urgent need to shift from fossil fuels to alternative sources of power that are reliable, sustainable, cost-effective, and environmentally friendly.

Additionally, concerns about energy security are driving efforts to develop and adopt renewable energy sources as viable replacements for dwindling fossil fuel reserves [1]. Additionally, a significant portion of the global population resides in remote or rural areas that are sparsely populated and geographically isolated. Due to low electricity demand, many of these communities remain unconnected to the main power grid. To facilitate development in such regions, there is a need for a well-structured and economically viable solution to provide access to electricity. Renewable energy sources offer a promising alternative, as they are environmentally friendly, cost-effective, and well-suited for powering off-grid areas [5]. Renewables like solar and wind energy are clean, abundant, and sustainable [6]. These characteristics have attracted significant interest from the energy sector, encouraging large-scale adoption of renewable technologies [7]. However, these sources are not without limitations. Their output is highly dependent on variable factors such as weather and climate, which can affect reliability.

Fortunately, the complementary nature of solar and wind energy allows for hybrid solutions where the weaknesses of one source are mitigated by the strengths of the other [7]. This leads to the concept of a hybrid microgrid power system and energy system that combines two or more sources, with at least one being renewable. The microgrid concept was initially introduced by the Consortium for Electric Reliability Technology Solutions (CERTS) in the United States. It represents a modern distributed generation network capable of operating either in isolation (islanded mode) or in coordination with the main grid. Microgrids typically include low-voltage distribution networks, distributed energy resources, energy storage, and controllable loads. Further research is needed to evaluate the practicality, cost-effectiveness, and potential benefits of deploying such systems in developing countries like Nigeria. This research aims to develop an Improved Grey Wolf Optimization Algorithm (IGWOA) for the optimal sizing of an isolated hybrid microgrid system comprising photovoltaic (PV) panels, wind turbines (WT), and battery energy storage (BES).

Optimal sizing is a critical aspect of microgrid design, as it ensures the system delivers reliable, sustainable, and cost-effective energy to end-users. It involves accurately determining the capacities and configurations of key components such as generation units, energy storage systems, and renewable energy sources to effectively meet energy demands while maximizing operational efficiency and minimizing overall costs. Therefore, this study aims to conduct an investigative analysis of the optimal sizing of a reliable hybrid microgrid system based on solar and wind energy for application in developing countries like Nigeria.

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Gwazaye community in Afaka ward of Igabi local government area is selected as the case study to assess the system's suitability, affordability, and acceptance

LITERATURE REVIEW

Microgrid

Integration microgrid systems of renewable energy (RE) sources into the power system has given rise to the concept of microgrid (MG) systems. The deployment of distributed generation (DG) units offers a practical solution to the challenge of inadequate power supply. One of the key advantages of distributed generation is the reduction in energy losses, as electricity is generated closer to the point of consumption, thereby minimizing transmission and distribution losses. The line power losses in a power system can be expressed as

$$P_{loss} = I^2 R \quad (1)$$

Where:

$P_{loss} = power\ loss\ in\ the\ system$
$I = current\ flowing\ through\ the\ line$
$R = resistance\ of\ the\ transmission\ line$

Despite its advantages, this alternative solution presents several challenges. The transition to a distributed energy network requires a shift from the traditional centralized monitoring system managed by a single control unit to a more advanced, decentralized monitoring approach. The integration of renewable energy resources (RERs) places additional strain on these monitoring systems due to the variable and intermittent nature of the natural resources they depend on. This intermittency often results in unpredictable power output, which can lead to network instability and imbalanced power supply. To mitigate these issues and enhance reliability, complementary RERs such as photovoltaic (PV) panels and wind turbines are often integrated with battery energy storage systems (BESS), enabling more stable and consistent energy delivery. The power balance equation for a micro grid system can be given as:

$$P_{load}(t) = P_{PV}(t) + P_{WT}(t) + P_{BESS}(t) + P_{grid}(t) \quad (2)$$

Where:

$P_{load}(t) = total\ load\ demand\ at\ time\ t$
$P_{PV}(t) = power\ output\ of\ the\ PV\ panels$
$P_{WT}(t) = power\ output\ of\ wind\ turbines$
$P_{BESS}(t) = power\ provided/stored\ by\ the\ energy\ storage\ system$
$P_{grid}(t) = power\ exchanged\ with\ the\ main\ grid\ (can\ be\ positive\ or\ negative)$

The microgrid (μ-grid) is widely regarded by the scientific community as a key component in the future of electrical power systems. Although there is no universally standardized definition or clearly defined scope, there is general consensus that a microgrid is a localized, small-scale power network that integrates various loads with distributed energy resources (DERs). Essentially, a microgrid is an independent electrical system that connects multiple energy users to distributed generation sources and energy storage systems (ESS), typically through power electronic converters. It is designed to operate either in grid-connected mode or independently (islanded mode) in a coordinated and controlled manner [8]. The power output of a PV system can be calculated as:

$$P_{PV} = G \times A \times \eta_{PV} \quad (3)$$

Where:

$G = solar\ irradiance\ (W/m^2)$
$A = area\ of\ the\ PV\ module\ (m^2)$
$\eta_{PV} = efficiency\ of\ the\ PV\ panel$

For wind turbine, the power output can be expressed as:

$$P_{WT} = \frac{1}{2} \times \rho \times A_{WT} \times v^3 \times C_p \quad (4)$$

Where:

$\rho = air\ density\ (kg/m^3)$
$A_{WT} = swept\ area\ of\ the\ wind\ turbine\ blades\ (m^2)$
$v = wind\ speed\ (m/s)$
$C_p = power\ coefficient\ of\ the\ turbine$

Distributed power generators can consist solely of renewable energy sources or be combined with conventional fossil fuel-based

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generators. Among renewable options, solar photovoltaic (PV) and wind turbines (WT) are two of the most prominent, with solar PV gaining widespread adoption due to significant cost reductions in recent years. However, the output power of renewable energy (RE) sources is generally less controllable compared to conventional generators. While conventional units rely on fossil fuels allowing system operators to regulate their output RE sources depend on natural phenomena, which are inherently variable and unpredictable.

Nevertheless, the integration of advanced power electronic converters can provide a degree of control over the output of RE systems [9]. Due to their stochastic, intermittent, and highly variable nature, integrating RE sources into the power grid especially at high penetration levels poses significant operational challenges. These include poor load-following capability, load mismatch, degraded power quality, frequency fluctuations, voltage instability, and reduced system reliability [10]. An effective strategy to address these challenges involves the use of energy storage systems (ESS), which store excess energy generated during periods of surplus and release it when demand exceeds supply [10][11].

$$P_{BESS}(t) = \begin{cases} \eta_{ch} \times P_{in}(t) & if\ charging \\ \frac{P_{out(t)}}{\eta_{dis}} & if\ discharging \end{cases} \quad 5$$

Where:

$P_{BESS}(t) = power\ stored/released\ by\ the\ BESS\ at\ time\ t$

$\eta_{ch} = charging\ efficiency$

$\eta_{dis} = discharging\ efficiency$

$P_{in}, P_{out} = input/output\ power\ to/from\ the\ battery$

The integration of energy storage systems (ESS) significantly enhances the performance of renewable energy (RE) sources by improving system reliability and power quality. ESS also facilitates reactive power control, power factor correction, voltage regulation, load leveling, load following, and the damping of power and frequency oscillations [12]. Among the various types of ESS available, battery energy storage systems (BESS) are the most widely used and considered the most promising option [13]. However, it is important to recognize that microgrids (MGs) incorporating RE sources and BESS typically involve higher capital costs. If these costs are excessive, the system may become commercially and industrially unattractive. Therefore, optimizing the sizing and operation of such microgrids to meet specific application constraints in a cost-effective manner remains a critical area of research. Addressing this challenge forms the core objective of this project.

Microgrid power quality

Power quality is a critical technical concern in microgrid systems, primarily due to the intermittent nature of integrated distributed renewable energy sources, transitions between grid-connected and islanded operational modes, the presence of nonlinear loads, harmonic currents introduced by power electronic devices, and loads with significant reactive power demand. To address these challenges and enhance power quality, researchers commonly employ strategies such as energy storage integration, harmonic filtering, and the implementation of advanced control schemes. The key indicators used to evaluate power quality include:

Voltage Total Harmonic Distortion (THD):

$$THD_V = \sqrt{\sum_{h=2}^{n} (\frac{V_h}{V_1})^2} \text{ X } 100\% \quad 6$$

Frequency Deviation:

$$\Delta f = f_{nominal} - f_{measured} \quad 7$$

Microgrid stability and protection.

Stability and protection represent additional critical technical challenges in microgrids, arising from factors such as reverse power flows from distributed generation units, local oscillations, transient operating modes, significant frequency deviations during islanded operation, and the economic and supply-demand uncertainties inherent in microgrid systems. Therefore, effective optimization, alongside appropriate control strategies and power management, is essential to ensure the efficient and reliable operation of hybrid microgrid systems. The **frequency stability** can be maintained using:

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$$P_{gen} - P_{load} = \frac{d\Delta f}{dt} \times H \quad (8)$$

Where H is the inertia constant.

Therefore, this thesis aims to achieve effective optimization of hybrid microgrid power systems, incorporating suitable energy storage devices for large-scale power generation. Such optimization is expected not only to complement the existing conventional power generation infrastructure but also to deliver a reliable, environmentally friendly, adequate, sustainable, and affordable power supply in Nigeria.

Classification Of Microgrid System (Mgs)

Basically, Microgrid System (MGS) can be classified into three (3) main groups namely remote, grid-connected and networked microgrid systems.

Remote Microgrid System

A remote microgrid system, also known as an off-grid or islanded microgrid, operates independently of the utility grid and remains in island mode at all times. This type of microgrid offers a cost-effective solution for supplying power to remote, sparsely populated, or geographically isolated areas located far from the main grid. In such settings, renewable energy sources like wind and solar are commonly combined to form a hybrid microgrid system (HMGS), providing a more economical, environmentally friendly, and sustainable distributed energy resource (DER) for rural communities. Additionally, battery energy storage systems are increasingly being adopted in place of conventional generators to help address the global warming challenges caused by greenhouse gas emissions from fossil fuels.

Grid-connected Microgrids

This type of microgrid is physically linked to the utility grid via a switching device at the point of common coupling (PCC), allowing it to operate either connected to the grid or independently in island mode as needed. When connected to the utility, a well-integrated microgrid can offer valuable grid services such as frequency and voltage regulation, real and reactive power support, and demand response, helping to mitigate issues related to capacity, power quality, reliability, and voltage stability on the main grid. In islanded operation, the microgrid requires local control of voltage and frequency, which can be managed through energy storage systems (like batteries or flywheels) or synchronous generators (such as combined heat and power units, natural gas, fuel cells, or diesel generators). Because battery energy storage systems provide both grid support functions and emergency backup power, they have become increasingly popular for microgrids that need to seamlessly switch between grid-connected and island modes. Grid-connected microgrids are particularly cost-effective when serving relatively small areas such as educational campuses, healthcare complexes, public safety facilities, military bases, farms, commercial buildings, and industrial sites.

Networked Microgrids

A networked microgrid, also referred to as a nested microgrid, comprises multiple independent Distributed Energy Resources (DERs) and/or individual microgrids interconnected within the same utility grid circuit segment, often covering an extensive geographic area. This system is typically overseen by a supervisory control system that manages and optimizes operations across various hierarchical levels, coordinating both grid-connected and islanded modes. Examples of networked microgrids include community microgrids, smart city infrastructures, and advanced utility adaptive protection schemes such as closed-loop self-healing systems.

4 Components of the Hybrid Solar and Wind Microgrid System

A Hybrid Microgrid System (HMGS) consists of key components such as wind turbines (WT), solar photovoltaic (PV) modules, a battery energy storage system (BESS), electronic converters, and controllable electrical loads, as illustrated in Figure 3.5 [14]. The following sections provide a brief overview of each major component.

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Wind Energy System

Wind energy is one of the most promising renewable energy sources capable of addressing the world's increasing power demands. It is a clean and environmentally friendly form of energy. Wind refers to the movement of air, and the kinetic energy contained in this motion is harnessed by wind turbines and converted into mechanical energy. This mechanical energy is then transformed into electrical energy through generators. Among the various types of generators used in wind energy systems, the most common are Permanent Magnet Synchronous Generators (PMSG) and Induction Generators (IG). In PMSGs, the excitation field is generated by permanent magnets instead of excitation coils, making them particularly suitable for commercial electricity generation. These are classified as synchronous generators because the rotor speed is synchronized with the grid frequency. PMSGs are widely preferred in high-power applications due to their high efficiency, low maintenance requirements, and the elimination of the need for a separate DC excitation source [15].

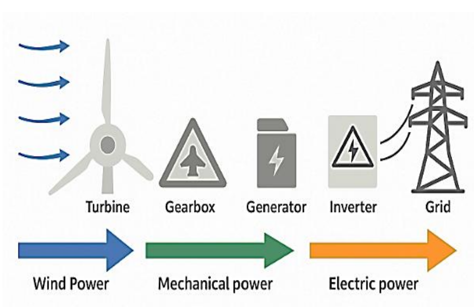

Figure 1: Wind Energy Schematic Diagram

Figure 2.1 illustrates the schematic layout of a wind energy generation system. The wind turbine comprises several key components, including the rotor, blades, gearbox, nacelle, generator, and tower. The nacelle, which is the central housing unit, contains both the gearbox and the generator. It is mounted atop the tower along with the rotor assembly. When wind flows over the blades, it imparts kinetic energy to the rotor hub. This rotational motion is transmitted through the gearbox, which increases the shaft speed to the level required by the generator.

PV Model

The power output of the PV module, PV module efficiency and the cell temperature can be determined by using equations 3.1, 8 and 9 respectively. [14]

$$P_{PV}(t) = \eta_{PV} * A_{PV} * G(t) \qquad 8$$

$$\eta_{PV} = \eta_{STC} * \eta_{MPPT}[1 - \alpha(T_C - T_{STC})] \qquad 9$$

$$T_C = T_a + \left[\frac{NOCT-20}{800}\right] * G(t) \qquad 10$$

Where **Apv** represents the surface area of the photovoltaic (PV) module in square meters (m²), **G(t)** is the hourly solar irradiance in watts per square meter (W/m²), **η_{pv}** denotes the overall efficiency of the PV module, **η_{stc}** is the reference efficiency of the PV cell under standard test conditions (STC), and **η_{mppt}** refers to the efficiency of the maximum power point tracker.

WT Model

The power output from a WT at time t depends on the wind speed and can be obtained from equation 3.4. (Traore, 2018)[14].

$$P_{WT} = \begin{cases} 0 & V(t) < V_{ci} \\ a.V^3(t) - b * P_{WT}{}^{Y} & V_{ci} \le V(t) < V_r \\ P_{WT}{}^{Y} & V_r \le V(t) < V_{co} \\ 0 & V(t) \ge V_{co} \end{cases} \qquad 12$$

Where;

$$a = \frac{P_{WT}{}^{Y}}{(V_r{}^3 - V_{ci}{}^3)}; \; b = \frac{V_{ci}{}^3}{(V_r{}^3 - V_{ci}{}^3)} \qquad 13$$

$V(t)$ *is the wind speed at time t in m/s*

P_{wt}^{r}, v_{ci}, v_r, and v_{co}, represent the rated power of wind turbine, the cut-in speed, rated speed and cut-out speed respectively.

Improved Grey Wolf Optimization (IGWO) Algorithm

The Grey Wolf Optimizer (GWO) is a population-based metaheuristic algorithm inspired by the natural leadership structure and hunting behaviour of grey wolves, as proposed in [21]. The social hierarchy of grey wolves is depicted in Figure 3.2 and can be summarized as follows.

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RESULTS

The simulation results are presented and analyzed in this section. Renewable energy data comprising wind speed, solar irradiance, and temperature were used to simulate the optimal sizing of an islanded hybrid microgrid designed to meet the electricity demand of a remote location in Kaduna State, Nigeria. This was done to evaluate the performance and effectiveness of the proposed Improved Grey Wolf Optimizer (IGWO) strategy. To verify the accuracy and robustness of the developed models and algorithm, a validation case was conducted by comparing the IGWO with four other optimization techniques: Particle Swarm Optimization (PSO), Differential Evolution (DE), Water Cycle Algorithm (WCA), and the standard Grey Wolf Optimizer (GWO).

Result Simulation

Case 1 Results and Discussion

In this scenario, the maximum permissible Loss of Power Supply Probability (LPSP) was set at 25%, and the Improved Grey Wolf Optimizer (IGWO) algorithm was executed using the previously defined input parameters. The resulting LPSP for Case 1 was 20.08%.

Figure 2 also shows that wind power generation is highly variable and stochastic. Consequently, the optimization algorithm tends to favor larger PV and BESS capacities relative to wind turbines. Lastly, the shape of the BESS power curve is largely dictated by the dominant renewable energy source at any given time, solar energy influences the curve during late morning to early evening, while wind energy has a greater effect during nighttime hours.

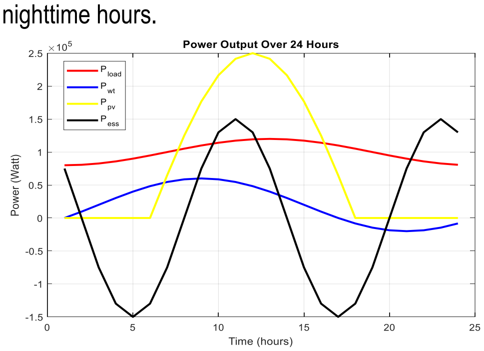

Figure 2: Mean Hourly Power Generation Optimum Schedule

A 2% difference between the energy charged and discharged by the BESS reflects system losses.

The dump load energy represents the surplus generation that could not be stored due to the limited capacity of the BESS. A total of 439.4 kWh of energy was not served accounting for 9% of total energy production and equivalent to 20.08% of total energy demand. Overall, the inherent variability of renewable energy sources necessitated the deployment of 917 kW of generation capacity and 386 kWh of storage capacity to satisfy at least 80% of the peak load demand of 162 kW.

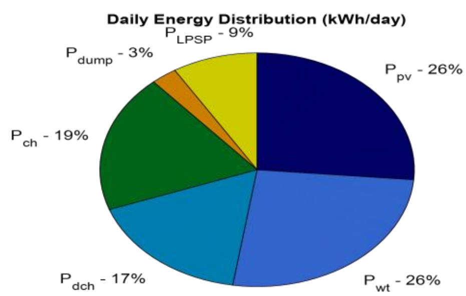

Figure 3: Energy Supply Mix Contributed by the Hybrid MG system

Simulation Results of Case 2

At an LPSP of 100%, the algorithm produced results identical to those obtained at 97% LPSP. As shown in Table 4.1, a general trend is observed: increasing the LPSP leads to a reduction in the installed capacities of the PV, wind turbine (WT), and battery energy storage system (BESS). This reduction in capacity lowers the total energy generation and subsequently results in a decrease in the overall system cost.

Capacities

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Table 1: Cost and Energy output with varying LPSP

LPSP (%)	Cost (₦/yr)	PV (kW)	PV Output (kWh)	WT (kW)	WT Output (kWh)	BESS (kW)	BESS (kWh)	Losses (kWh)
97	3,786,175.00	14	32	11	35	0	0	0
88	18,173,640.00	68	163	50	170	0	0	0
79	34,075,575.00	145	350	84	284	0	0	0
69	54,672,367.00	167	405	157	542	40	40	10
58	79,055,334.00	185	450	240	820	115	115	30
48	106,618,688.00	180	438	345	1180	210	210	75
39	125,246,669.00	570	1390	160	558	100	320	100
28	182,645,082.00	185	448	550	1920	410	650	215
19	223,535,772.00	180	445	670	2310	520	900	295
8	245,192,693.00	940	2300	230	810	270	1140	350
1	257,308,453.00	425	1040	680	2340	530	920	385
0	246,555,716.00	740	1810	460	1610	330	850	385

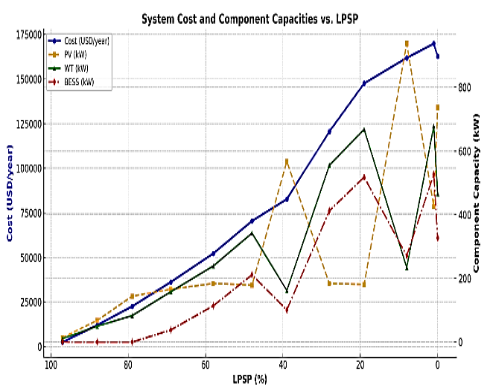

Figure 4: Variation of EPI with Increase in LPSP.

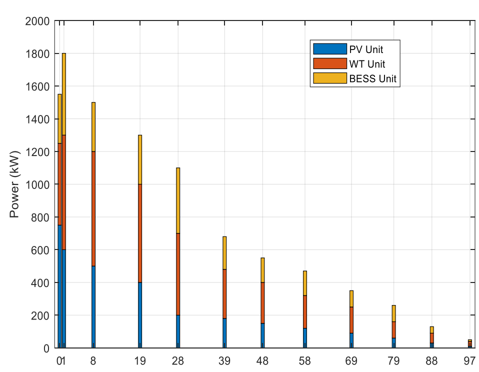

Figure 5: PV, BESS and WT installed capacities

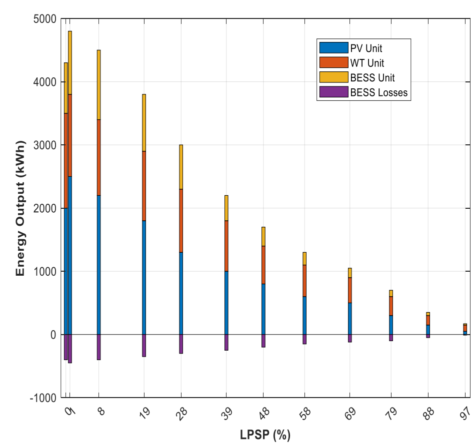

Figure 6: BESS Losses and Total Energy Production

Further technical and economic details on these configurations are available in [32]. This case study compares the performance of the proposed IGWO algorithm against four other optimization methods: Particle Swarm Optimization (PSO), Differential Evolution (DE), Water Cycle Algorithm (WCA), and the conventional Grey Wolf Optimizer (GWO).

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Table 2: NPV comparison for different approaches

Configuration	Algorithm	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
DG-FT	PSO	8	8	8.01	8	8	8.01	8	8	8	8
	DE	8	8	7.99	8	8	8	8	8.01	8	8
	WCA	8	7.99	8	8	8	8	8	8	7.99	8
	GWO	8	8	8	7.99	8	8	8	8	8	8
	IGWO	8	8	8	8	8	8	8.01	8	8	8
DG-FT-PV-WT	PSO	8.02	8.06	8.02	8.02	8.06	8.02	8.02	8.04	8.02	8.02
	DE	8.05	8.06	8.05	8.05	8.06	8.05	8.06	8.05	8.05	8.05
	WCA	8.02	8.02	8.04	8.02	8.05	8.04	8.05	8.02	8.02	8.02
	GWO	8.02	8.02	8.02	8.02	8.05	8.02	8.04	8.02	8.05	8.02
	IGWO	8.04	8.04	8.05	8.03	8.05	8.05	8.06	8.05	8.04	8.04
DG-FT-PV-WT-BB	PSO	6.94	7.03	6.94	6.94	6.96	6.97	6.99	6.94	6.94	6.94
	DE	7.70	7.76	7.80	7.70	7.73	7.74	7.78	7.70	7.71	7.70
	WCA	7.20	7.20	7.26	7.29	7.36	7.20	7.33	7.33	7.20	7.20
	GWO	6.97	6.94	6.94	7.00	6.96	6.94	6.94	7.02	6.94	6.97
	IGWO	6.95	6.95	6.97	7.03	7	6.87	6.97	6.99	6.87	6.93
PV-WT-BB	PSO	11.69	11.69	11.69	11.71	11.69	11.69	11.69	11.71	11.69	11.71
	DE	12.08	12.1	12.08	12.08	12.08	12.1	12.08	12.15	12.08	12.13
	WCA	11.91	11.85	11.9	11.85	11.87	11.85	11.85	11.85	11.89	11.85
	GWO	11.69	11.69	11.69	11.71	11.69	11.7	11.69	11.69	11.71	11.69
	IGWO	11.74	11.72	11.74	11.74	11.73	11.73	11.72	11.72	11.74	11.72

Table 4.3 shows the Net Present Value (NPV) results for the overall system across 10 consecutive runs using various metaheuristic algorithms. It was observed that the inclusion of PV and WT components leads to fluctuations in NPV across runs, likely due to the inherent variability in renewable energy resources. For the DG-FT configuration, the NPV remained constant at 8.00 for all iterations. However, incorporating renewable sources resulted in a slight reduction in NPV, while excluding the diesel generator led to a significantly higher NPV. Among the methods evaluated, the proposed IGWO algorithm achieved lower NPV values compared to some other algorithms, demonstrating its effectiveness for optimal microgrid sizing.

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Table 3 Energy Production, and Fuel Consumption comparison

Configuration	Algorithm	Diesel Gen (MWh)	Renewable Gen (MWh)	Fuel Use (kL)	CO_2 Emission (tons)	Dumped Energy (MWh)
DG-FT	PSO	1260.52	N/A	427.64	1159	53.15
	DE	1259.3	N/A	427.5	1157.8	53.7
	WCA	1265.1	N/A	430.2	1166.9	54.8
	GWO	1261.4	N/A	428.1	1160.2	53.9
	IGWO	1260.25	N/A	427.85	1158.7	54
DG-FT-PV-WT	PSO	1230.19	96.95	417.68	1130	118.75
	DE	1248.9	34.55	423.75	1148.5	78.4
	WCA	1227.85	110.1	417.2	1129.8	122.65
	GWO	1230.1	104.5	416.9	1132.5	121.2
	IGWO	1235.35	92.4	419.85	1137.3	118.45
DG-FT-PV-WT-BB	PSO	607.57	854.64	206.57	559.74	232.1
	DE	955.8	316.75	323.45	878.5	56.75

Table 4: Percentage Improvement

Techniques	NPV (System Cost)	Improvement
PSO	6.94	0.14% lower
IGWO	6.93	
DE	7.7	10% lower
IGWO	6.93	
WCA	7.2	3.8% lower
IGWO	6.93	
GWO	6.97	0.6% lower
IGWO	6.93	

CONCLUSION

A hybrid islanded microgrid system has been proposed to generate electricity for a rural community in Kaduna State, Nigeria. This study comprehensively reviewed key research efforts related to the optimization of islanded microgrid distributed energy resources, including solar photovoltaic (PV), wind turbines (WT), and battery energy storage systems (BESS). Ten years' worth of relevant data, solar irradiance, wind speed, ambient temperature, and electricity demand were successfully gathered and utilized. The Improved Grey Wolf Optimization Algorithm (IGWOA) was applied alongside four developed models.

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