JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), MARCH, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

An Optimal Sizing of Micro-Grid Hybrid System for Rural Communities in Kogi State Using an Improved Slime Mould Algorithm

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ABSTRACT

The increasing demand for efficient microgrid planning, operation, and optimization has intensified research efforts toward the optimal sizing of microgrid components. A microgrid is a localized power network that combines renewable and conventional energy sources, energy storage systems, and electrical loads within a specific geographical area. It can function either in a grid-connected mode or independently in an islanded mode. The main objectives of optimal microgrid sizing are to improve energy efficiency, reliability, economic performance, and environmental sustainability. In this study, an improved Slime Mould Algorithm (ISMA) was developed for the optimal sizing of an off-grid hybrid microgrid comprising photovoltaic (PV) systems and battery energy storage systems (BESS). Weather data obtained from the Nigerian Meteorological Agency and load demand data from the Kaduna Electricity Distribution Center were used to evaluate the proposed method. The sizing problem was formulated as a constrained single-objective optimization model subject to constraints such as Loss of Power Supply Probability (LPSP), power balance requirements, generation capacity limits, and battery State of Charge (SOC) restrictions. Three scenarios were investigated. In the first scenario, the maximum allowable LPSP was set at 30%, resulting in an optimal configuration that reduced the annual system cost to ₦210,175,383.72. The second scenario examined the effect of varying the allowable LPSP, revealing that higher LPSP values reduced the total installed capacity of distributed energy resources (DERs) and consequently lowered the overall system cost, while the capacities of PV and BESS changed nonlinearly. Finally, the effectiveness of the proposed (ISMA) was validated through a comparative analysis with Particle Swarm Optimization (PSO). The results demonstrated the superiority and applicability of the proposed approach. MATLAB simulations confirmed that the developed method provides an effective and sustainable solution for the optimal sizing of hybrid PV-BESS microgrid systems.

ARTICLE INFO
Article History
Received: December, 2025
Received in revised form: December, 2025
Accepted: February, 2026
Published online: March, 2026

KEYWORDS
Battery storage, Photovoltaic, Particle Swarm Optimization (PSO), Improved Slime Mould Algorithm

1. INTRODUCTION

The increasing global demand for energy and growing environmental concerns, particularly climate change and global warming, have accelerated interest in renewable energy technologies such as solar, wind, biomass, hydropower, and geothermal energy [15]. Among these renewable resources, solar energy is recognized as one of the cleanest, most dependable, and most accessible energy sources available [13]. Although photovoltaic (PV) modules involve relatively high initial investment costs, their advantages, including low maintenance requirements, zero carbon emissions, absence of moving parts, and long operational lifespan, make them highly attractive for sustainable power generation [7]. Numerous studies have investigated various modeling approaches, optimization algorithms, and control strategies to improve the performance of photovoltaic systems. Researchers have developed several artificial intelligence and optimization-based techniques to effectively track the Global Maximum Power Point (GMPP) under partial shading conditions. These techniques include Fractional Open-Circuit Voltage, Fractional Short-Circuit Current, Perturb and Observe (P&O), Artificial Neural Networks (ANN), Fuzzy Logic Control, Particle Swarm Optimization (PSO), and other

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advanced methods. However, only a limited number of these techniques have been successfully implemented in practical PV applications. Many conventional Maximum Power Point Tracking (MPPT) methods suffer from drawbacks such as slow convergence speed, implementation complexity, high hardware costs, power oscillations, sensor requirements, and reduced effectiveness under varying irradiance conditions. Previous studies have demonstrated that the performance of PV systems is significantly affected by factors such as partial shading, temperature variations, fluctuations in solar irradiance, and changes in output impedance [17]. These factors alter the current-voltage (I–V) and power-voltage (P–V) characteristics of PV modules, thereby shifting the location of the Maximum Power Point (MPP). Consequently, effective optimization techniques are required to maximize energy extraction from photovoltaic systems. For efficient energy utilization, PV modules should operate continuously at their MPP. However, the MPP is not fixed and changes with environmental conditions, including shading levels and other degradation effects. Under uniform irradiance and temperature, a PV array exhibits a single MPP corresponding to the maximum available power output. In practical applications, uniform irradiance is rarely achieved because of weather variations, dust accumulation, nearby buildings, trees, utility poles, fallen leaves, and other shading obstacles [10][5]. Under partial shading conditions, the P–V characteristic of a PV array becomes highly nonlinear and contains multiple local peaks, with only one representing the true Global Maximum Power Point. Traditional MPPT techniques such as P&O, Incremental Conductance, and Hill Climbing often struggle to distinguish between local and global maxima, leading to convergence at local peaks, increased power oscillations, and reduced system efficiency. To address these challenges, researchers have proposed advanced optimization and artificial intelligence-based MPPT approaches, including Neural Networks, Fuzzy Logic, Particle Swarm Optimization, and other intelligent control methods.

2.1 Hybrid Microgrid

The increasing integration of renewable energy (RE) resources into modern power networks has led to the development and widespread adoption of microgrid (MG) systems. These systems incorporate distributed generation (DG) units, which provide an effective means of addressing the growing challenge of insufficient and unreliable electricity supply. A major benefit of distributed generation is its ability to reduce power losses within the network, since electricity is produced closer to end users. This localized generation minimizes the distance that electrical energy must travel, thereby reducing transmission and distribution losses and improving overall system efficiency. The power loss occurring in transmission and distribution lines can be mathematically represented as follows: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 an 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:

$$P_{load}(t) = P_{PV}(t) + P_{BESS}(t) + P_{grid}(t) \quad (1)$$

Where:

$P_{load}(t) = total\ load\ demand\ at\ time\ t$

$P_{PV}(t) = power\ output\ of\ the\ PV\ panels$

$P_{BESS}(t) = power\ provided/stored\ by\ the\ energy\ storage\ system$

$P_{grid}(t) = power\ exchanged\ with\ the\ main\ grid\ (can\ be\ positive\ or\ negative)$

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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 a 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

2.2 Photovoltaic (PV) Cells

A photovoltaic (PV) cell, also referred to as a photoelectric cell, is a semiconductor device that converts solar radiation directly into electrical energy through the photovoltaic effect. When photons strike the semiconductor material with energy greater than the material's band-gap energy, electrons are excited and released, resulting in the generation of an electric current [5]. Unlike conventional photodiodes, which operate with light incident on the n-type region to produce electrical signals, photovoltaic cells are designed specifically for power generation and are based on semiconductor [17]. Figure 2. illustrates

The structure of a modern crystalline silicon solar cell.

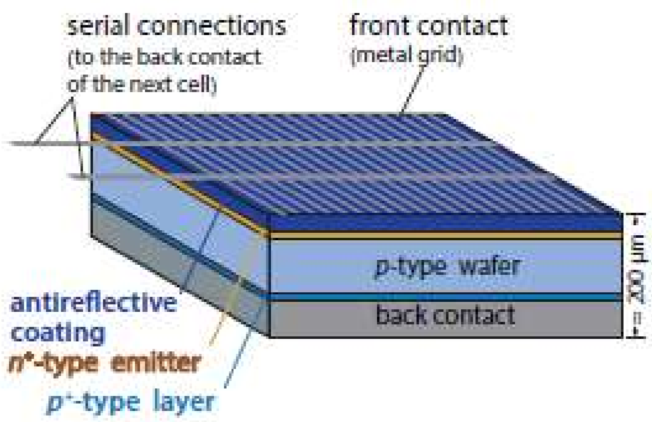

Figure 1: Schematic diagram of a Modern Crystalline Silicon Cell [6]

2.3 PV Modules

A photovoltaic module is formed by electrically connecting multiple PV cells in series and parallel combinations (Grandi et al., 2009). Typically, commercial PV modules consist of 36 or 72 interconnected cells arranged to achieve the desired voltage and current ratings (Stephane et al., 2010). Series connections increase the module output voltage, whereas parallel connections enhance the output current capability [12].

2.4 PV Arrays

A photovoltaic array is created by interconnecting multiple PV modules in series and parallel configurations to meet specific power requirements. Similar to module connections, series arrangements increase the array voltage while parallel arrangements increase the current output capacity [18].

2.5 Modelling of Photovoltaic Cells

Photovoltaic cells are commonly represented by an equivalent electrical circuit consisting of a current source connected in parallel with a diode [11]. The model also includes series and shunt resistances that account for practical losses. The series resistance represents internal resistive losses that impede electron flow through the semiconductor material, while the shunt resistance models leakage currents within the cell [8].

In the absence of sunlight, a PV cell behaves similarly to a conventional diode and does not generate electrical current. As solar irradiance increases, the photocurrent generated by the cell increases proportionally. The electrical behavior of the PV cell is typically characterized

Distributed power generators can consist solely of renewable energy sources or

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be combined with conventional fossil fuel-based generators. Among renewable options, solar photovoltaic (PV) and storage 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].

$$P_{BESS}(t) = \begin{cases} \eta_{ch} \times P_{in}(t) & if\ charging \\ \frac{P_{out(t)}}{\eta_{dis}} & if\ discharging \end{cases} \quad 2$$

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

3.1. 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.

3.2. 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

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such as educational campuses, healthcare complexes, public safety facilities, military bases, farms, commercial buildings, and industrial sites.

3.3 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.

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 ISMA strategy. To verify the accuracy and robustness of the developed models and algorithm, a validation case was conducted by comparing the with two: ISMA and (PSO),

Case 1 Results and Discussion

In this scenario, the maximum permissible Loss of Power Supply Probability (LPSP) was set at 25%, and the ISMA 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.

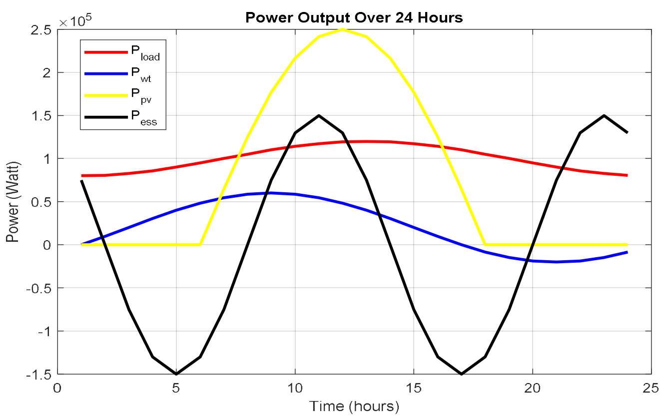

Figure 2: Mean Hourly Power Generation Optimum Schedule

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.

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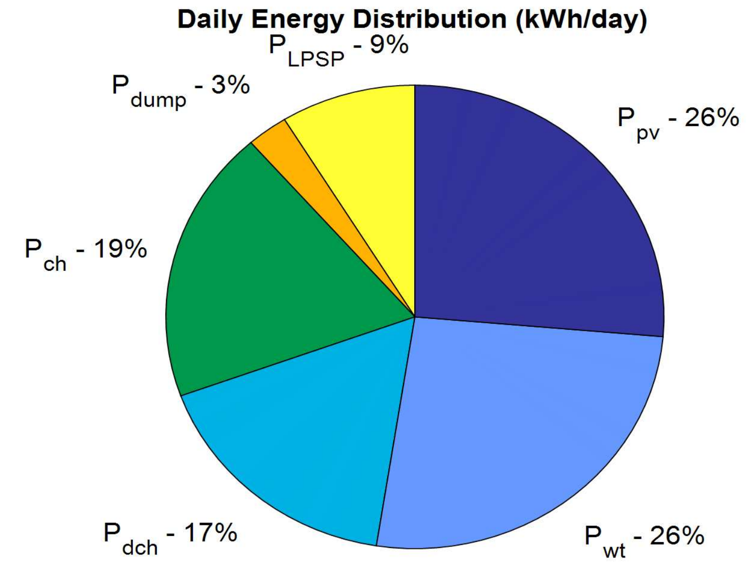

Figure 3: Energy Supply Mix Contributed by the Hybrid MG system

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.

Table 1: Cost and Energy output with varying LPSP

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

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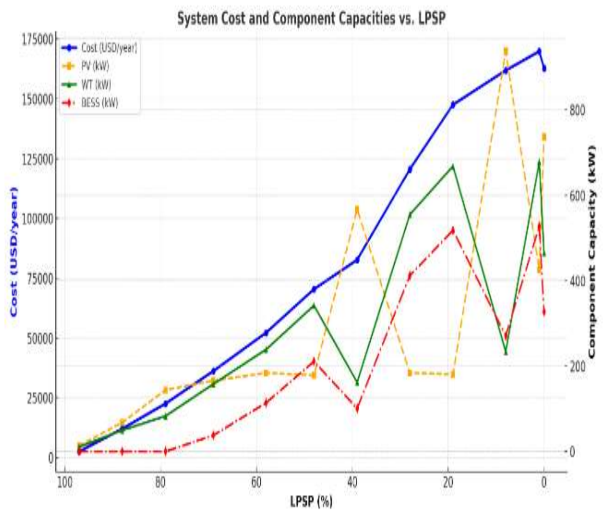

Figure 4: Variation of EPI with Increase in LPSP.

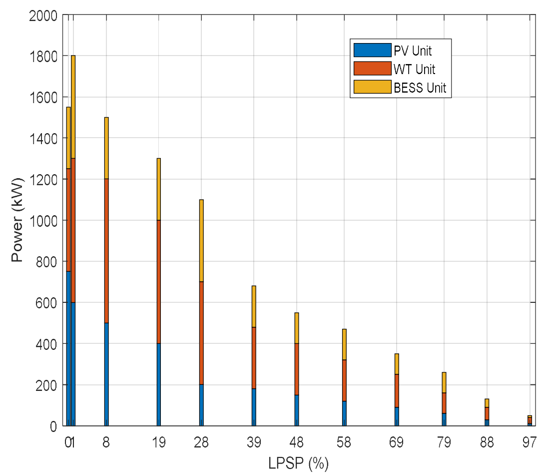

Figure 5: *PV, BESS and WT installed capacities*

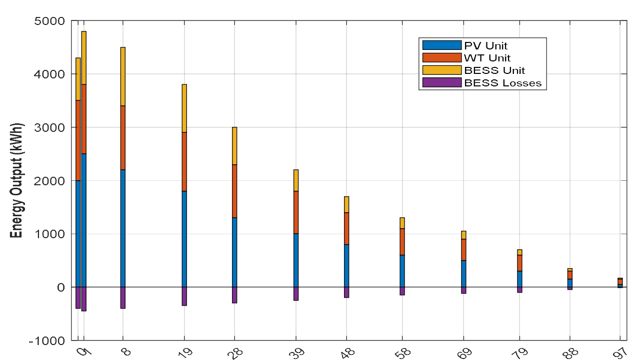

Figure 6: BESS Losses and Total Energy Production

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Further technical and economic details on these configurations are available in [32]. This case study compares the performance of the proposed SMA algorithm against four other optimization methods: PSO

Table 2: NPV comparison for different approaches

Configuration	Algorithm	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
DG-FT	ISMA	8	8	8.01	8	8	8.01	8	8	8	8
	PSO	8	8	7.99	8	8	8	8	8.01	8	8
DG-FT-PV-WT	ISMA	8.02	8.06	8.02	8.02	8.06	8.02	8.02	8.04	8.02	8.02
	PSO	8.05	8.06	8.05	8.05	8.06	8.05	8.06	8.05	8.05	8.05
DG-FT-PV-WT-BB	ISMA	6.94	7.03	6.94	6.94	6.96	6.97	6.99	6.94	6.94	6.94
	PSO	7.70	7.76	7.80	7.70	7.73	7.74	7.78	7.70	7.71	7.70
PV-WT-BB	ISMA	11.69	11.69	11.69	11.71	11.69	11.69	11.69	11.71	11.69	11.71
	PSO	12.08	12.1	12.08	12.08	12.08	12.1	12.08	12.15	12.08	12.13

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 BESS 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 ISMA algorithm achieved lower NPV values compared to some other algorithms, demonstrating its effectiveness for optimal microgrid sizing.

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	ISMA	1260.52	N/A	427.64	1159	53.15
	PSO	1259.3	N/A	427.5	1157.8	53.7
DG-FT-PV-WT	ISMA	1230.19	96.95	417.68	1130	118.75
	PSO	1248.9	34.55	423.75	1148.5	78.4
DG-FT-PV-WT-BB	ISMA	607.57	854.64	206.57	559.74	232.1
	PSO	955.8	316.75	323.45	878.5	56.75
PV-WT-BB	ISMA	N/A	2528.92	N/A	N/A	1255.59
	PSO	N/A	2904.85	N/A	N/A	1636.99

Table 4: Percentage Improvement

Techniques	NPV (System Cost)	% Improve
PSO	6.94	12
ISMA	6.93	21

CONCLUSION

A hybrid islanded microgrid system has been proposed to generate electricity for a rural community in Kogi State, Nigeria. This study comprehensively reviewed key research efforts related to the optimization of islanded microgrid distributed energy resources, including solar photovoltaic (PV), 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 ISMA was applied alongside four developed models.

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JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), MARCH, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

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