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**Research Paper**

# Decentralized Smart Energy Management in Hybrid Microgrids: An Evaluation of Operational Modes, Resource Optimization, and Environmental Impacts in Nigeria

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***ABSTRACT***

*Escalating energy demands and climate change challenges necessitate the adaptation of renewable-based microgrid systems in the energy sector. The proposed work employs a robust Multi Agent System (MAS) technique to achieve efficient and automated control of the hybrid microgrid operation. The hybrid microgrid system incorporates Renewable Energy Sources (RES), a diesel generator, and a battery storage system. The operation of the hybrid microgrid consists of three distinct modes: islanded, transition to grid, and grid-oriented mode. The system's performance is optimized by considering factors like climatic patterns, energy costs, connected source characteristics, and load demand. Different climatic scenarios are assessed for each mode of operation, where the best, extreme sunny, extreme cloudy, and worst climate conditions are considered for islanded mode; sunny and cloudy scenarios are considered for transition to grid mode as well as grid-feed and grid-tied modes are considered for grid-oriented operation of the microgrid. The simulation studies are performed using the MATLAB/Simulink R2021a environment. Furthermore, Particle Swarm Optimization (PSO) is implemented to optimize power allocation within the microgrid and enhance its cost-effectiveness. The optimization results demonstrate efficient utilization of available energy sources along with effective energy management facilitated by the MAS control system. The results emphasize the importance of adopting a MAS approach for achieving smart energy management through comprehensive analysis and integrating decentralized energy management techniques for optimal accommodation of distributed energy resources in hybrid microgrids.*

***INDEX TERMS:*** *Renewable energy sources, particle swarm optimization, energy management system, multi agent system, microgrid.*

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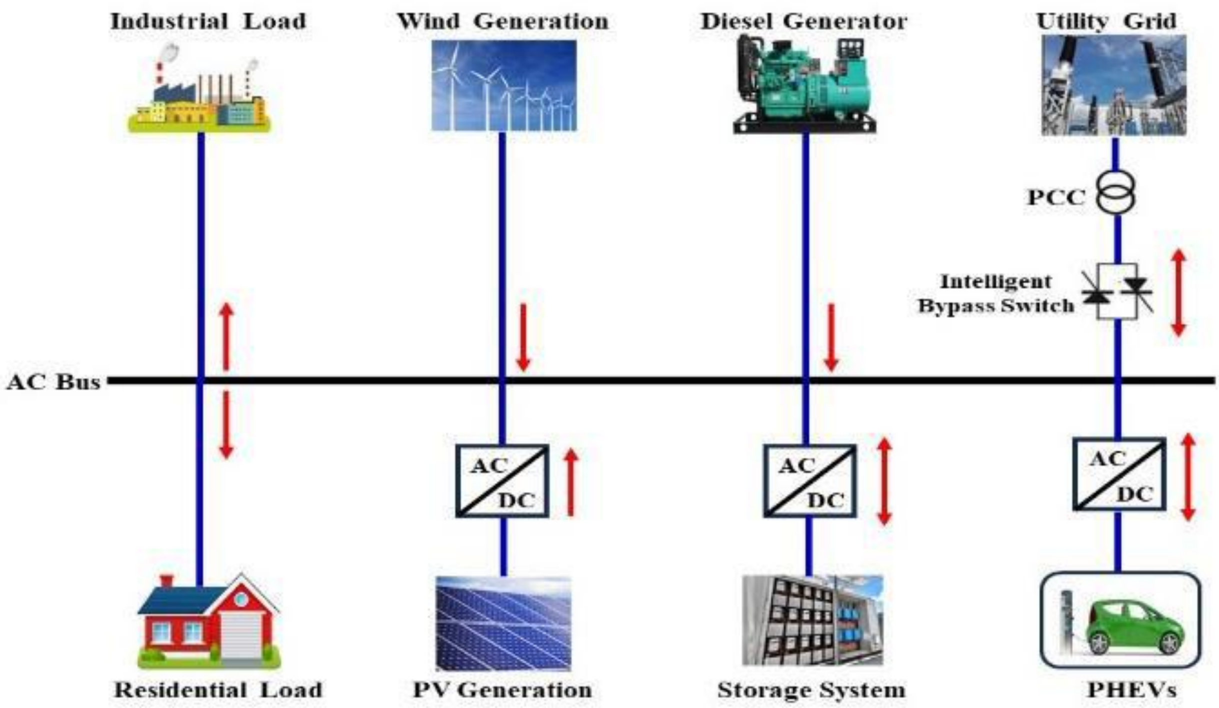
**NOMENCLATURE**

RES Renewable energy sources.
DER Distributed energy resources.
PV Photovoltaic.
MAS Multi agent system.
PSO Particle swarm optimization.
AI Artificial intelligence.
MILP Mixed integer linear programming.
TOU Time of Use.
RAP Particle swarm optimization.
DLC Direct load control.
MBA Modified bat algorithm.
SSA Salp swarm algorithm.
EMS Energy management system.
DSM Demand side management.
DG Distributed generator.

CA Control automation.
Sim Simulation.
Opt Optimization.
Cp Cost per watts.
Op Operation & maintenance cost.
PPV Power generated by the wind power system.
CW Cost per watts.
OW Operation & maintenance cost.
PWT Power generated by the wind power system.
ρ Operating cost (0.008 $/kWh).
PD Power generated by diesel generator.
dt Step.
PDG Price of diesel generator.
NDG Number of diesel generators.
fr Inflation rate.
ir Interest rate.
σD Hot startup.
δD Cold startup.
TOFF,D Off time.
TD Cooling time.
u(t−1),D Status of diesel generator.
CG Price of the unit offered by the utility Grid.
PG Power of the utility grid.
O&M Operation and maintenance.
LCOE Levelized cost of energy.
CDG Cost of fuel.
FD Amount of fuel consumed.
Cdiesel Price of diesel.




# I. INTRODUCTION

The global increase in carbon emissions from anthropogenic activities is severely leading to global warming with an increase in temperature, causing severe climate change. According to the 6th report from the Intergovernmental Panel on Climate Change (IPCC), a 2°C increase in the global temperature is expected around 2040. Thus, the 2021 IPCC report has issued an early alarm that the earth's warming beyond 1.5°C will have detrimental effects on the planet, causing sea level rise, droughts, and floods [1]. It has also recommended switching from fossil fuels to Renewable Energy Sources (RES) for energy generation and consumption. According to SDG 7, access to clean and affordable energy is the right of every household. Hence, this can be ensured by developing alternative energy sources that can tackle climate change related challenges and overcome the energy supply and demand gap. The microgrid seems to be a viable option as it utilizes RES and other small generation sources compared to a traditional power grid (primarily dependent on conventional energy sources) [2]. A generalized structure of a microgrid model is presented in Figure 1.

Implementing renewable energy-based technologies to improve the energy efficiency of the current power systems is among the alternatives discussed for climate change mitigation and adaptation by the energy sector [3]. Adefarati and Bansal [4] studied RES environmental and economic impacts and their feasibility in a microgrid system. The proposed study demonstrates that using RES in a microgrid can reduce several extreme factors like GHG emissions, peak energy costs, load demand fluctuations, and load side losses. Blake and O'Sullivan [5] discussed the impacts of integrating RES with an industrial microgrid by considering key parameters like energy costs and GHG emissions. The study's results demonstrate a significant drop in energy costs, decreased carbon footprints and reduced GHG emissions. Hence, RES are the best remedy to achieve cost savings and environmental benefits; however, RES, like solar and wind, have a stochastic nature that varies according to climatic conditions.

Luo et al. [6] discussed the intermittent nature of wind and PV concerning grid power dispatching using a short-term-based hybrid model that effectively compensates the forecast errors and provides uninterruptable power to load. Prajapati and Mahajan [7] proposed Demand Response Programs (DRPs) to address the uncertainties of RES and congestion management problems in microgrid operation. Wang et al. [8] considered three loads with different DRPs based on RES uncertainty, Energy Storage System (ESS), and the cost function based on market price using the PSO algorithm. The results indicate the benefits of DR, a 3.4% enhancement in voltage profile and a 20-30% decrease in total cost. Similarly, Jiao et al. [9] proposed a multi-objective model to provide a trade-off solution between maximum profits and minimum risks by considering the uncertainties involving solar and wind RES in a standalone microgrid. The proposed model can create coordination between diesel generator, PV and wind power that improves penetration of RES and maximizes the profit in standalone microgrid operation and planning. Ramadan et al. [10] considered the intermittent nature of RES and its impact on the loads based on the optimal placement and sizing of RES in a radial system using the Artificial Hummingbird algorithm. The results of the study indicate significant improvement in the parameters of the distribution bus systems.

Moreover, the energy management system control of microgrids enables managing the uncertainties of RES sources effectively and simultaneously controls the balance between energy demand and consumption. Khan et al. [11] provided insight into the operations and impacts of multi-source-based microgrids by discussing their various architectures, control strategies for their reliable operations and the solutions for meeting the requirements of their control and communication. Anvari-Moghaddam et al. [12] suggested an energy management control structure for monitoring and controlling microgrid operation in real-time through MAS based on defined standards. Results show that the suggested approach addresses the consumer's demand during uncertainties and reduces energy costs, thus ensuring optimal microgrid operation. Alam et al. [13] proposed an energy management control strategy by considering a DC microgrid in which RES and ESS are integrated. Results indicate that the integration of RES and ESS is reliable when it meets the load demand in case of transient conditions like fluctuations in the power generation of RES and abrupt changes in the load demand. Further, the researchers in [14] suggested that a stand-alone microgrid with its controllers can serve as a gateway for supplying power to remote areas without access to the utility grid. The microgrid control strategy is designed so that when the RES can't meet the load demand, the ESS provides extra power to fulfill the load demand.

Similarly, different research studies have proposed many approaches to schedule and adequately distribute the power generation from RES. Implementing an energy management system utilizing MAS can provide a reliable solution for microgrids to supply power to loads to fulfill energy demands. Kofinas et al. [15] proposed a Fuzzy Q-Learning energy management control strategy to ensure real-time control and monitoring of microgrid operations. Salam et al. [16] proposed a microgrid model based on centralized MAS control by dividing the load into critical and non-critical loads. The RES is scheduled by utilizing the Demand Side Management (DSM) technique such that the non-critical load sheds its power to support the critical load in case of low power supply to the critical load.

Jabeur et al. [17] considered a microgrid comprising PV and ESS and proposed its application for smart homes. By implementing MAS, the microgrid agents can communicate and function according to the changes in system configuration due to uncertain situations like changes in solar irradiance and variations in battery State of Charge (SoC). Moreover, Wang et al. [18] developed a communication mechanism that combines MAS and microgrid control to optimize microgrid operation. The Multi Agent Chaotic Particle Swarm Optimization (MACPSO) algorithm is designed to optimize storage techniques by considering a time-based electrical power price mechanism. The result of the proposed model indicates a reduction in environmental and operation costs.

Boussaada et al. [19] have proposed an energy management system model based on the MAS technique for an islanded microgrid that supplies a sailboat using RES. AI techniques are also utilized to ensure the security of microgrid agents, real-time user interface updates, and prediction of the energy produced by the RES. The results demonstrate the model's efficiency and better security by considering the constraints of the sailboat. Abdelsalam et al. [20] considered three microgrids and employed MAS and DSM techniques for power management between them and controlling the load during different time intervals related to tariffs. Study results demonstrate reduced prices in consumer electric bills and minimization of the peak load demand.

Shi et al. [21] proposed a ring-based MAS strategy for controlling microgrid operation and improving performance by suggesting a reward-based control structure for MAS using an autonomous microgrid operation technique. Zhang et al. [22] proposed an energy management strategy to mitigate the uncertainties of microgrid power generation by providing a stochastic solution for each agent to supply its respective load demand and balance the overall microgrid power demand and supply during uncertainties. Results demonstrate that MAS can provide real-time system control for microgrids, improve energy efficiency, and achieve reliable power supply with reduced load demand, supply losses and cost.

Similarly, Ali et al. [23] have considered the impact of MAS on RES uncertainty and developed a microgrid control and monitoring strategy using the PSO technique. The PSO technique enables each agent to participate in the microgrid operations, thereby ensuring reliable operation. Mohamed et al. [24] proposed a control strategy for the operation of a grid-connected microgrid using MAS. The study uses PSO to optimize the design and placement of RES, ensuring optimal use of available energy sources and fulfilling the energy demand while reducing costs.

The literature review indicates the significance of MAS in controlling and optimizing microgrid operation with reduced GHG emissions, operation costs, and peak load demand by enhancing the efficiency of RES [24]. The primary purpose of this paper is to evaluate the operational modes, resource optimization, and environmental impacts of MAS-based energy management in hybrid microgrids. The hybrid microgrid model includes RES, diesel generators, and battery storage systems. The operational modes of the hybrid microgrid are categorized into three primary modes: islanded, transition to grid, and grid-oriented. The proposed study evaluates the impact of climatic conditions on each mode, optimizing resource allocation using PSO to achieve efficient energy management. Simulation studies are performed in the MATLAB/Simulink R2021a environment, and results demonstrate the effectiveness of the MAS approach in achieving optimal energy management in hybrid microgrids.

**TABLE 1. Literature analysis table.**

**Note:** CA = Control Automation, Sim = Simulation, Opt = Optimization, DLC = Direct Load Control, PSO = Particle Swarm Opti
[P] = Proposed Study

| Paper | Operation | | Strategy | | Techniques | | | Outcomes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Islanded | Grid | Sim | Opt | MAS | PSO | DLC | Power Scheduling | Cost Scheduling | CA | Weather Forecasting |
| [12] | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | |
| [13] | ✓ | | ✓ | | | | | ✓ | | | |
| [14] | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ | |
| [15] | ✓ | | | ✓ | ✓ | | | ✓ | | | |
| [16] | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ | |
| [17] | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | | |
| [18] | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| [20] | ✓ | | | ✓ | ✓ | | | ✓ | ✓ | | |
| [21] | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | ✓ | |
| [22] | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | |
| [23] | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ | |
| [24] | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | |
| [25] | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | | |
| [30] | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ |
| [31] | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ |
| [32] | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | | |
| [33] | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | |
| [34] | ✓ | ✓ | | ✓ | | ✓ | | ✓ | ✓ | | ✓ |
| [36] | ✓ | | ✓ | ✓ | | ✓ | | ✓ | | | ✓ |
| **[P]** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## II. Materials and Methods

*Microgrid Description*

- **Components**: The microgrid includes AC and DC sources, managed through a MAS (Multi-Agent System) control technique.
- **Agents**:
  - **Source Agent**: Includes PV, wind power system, ESS (Energy Storage System), and diesel generator.
  - **Load Agent**: Comprises industrial and residential loads (5 kW each, totaling 10 kW). Industrial loads are prioritized.
  - **Grid Agent**: Represents the utility grid, providing support during uncertain conditions.
- **Control**: Managed by a MAS controller, which schedules and coordinates agents based on local information and interactions.
- **PSO Implementation**: Used for power and cost optimization of the microgrid.

*PV (Photovoltaic)*

- **Model**: Trina Solar TSM-250PA05.08, rated at 9 kW.
- **Operation**: Uses a boost converter and MPPT (Maximum Power Point Tracking) controller to maximize power output.
- **Cost Function**: $CPV=(C_P+O_P)P_{PVC}$

Where CPC_PCP is the cost per watt, OPO_POP is the operation & maintenance cost, and PPVP_PPV is the power generated by the PV system.

*Wind Power*

The wind power system comprises of wind turbines that actas prime movers and are coupled to the shafts of the generatorsused. The kinetic energy of the wind spins the turbinesof the wind turbine and produces mechanical energy. Themechanical energy is converted into electrical energy throughthe generators connected further to wind turbines [37]. Thepower produced by wind turbines depends upon the windspeed and the installed capacity of the generators connected.

Eq. (2) can show the cost function of the wind power system.

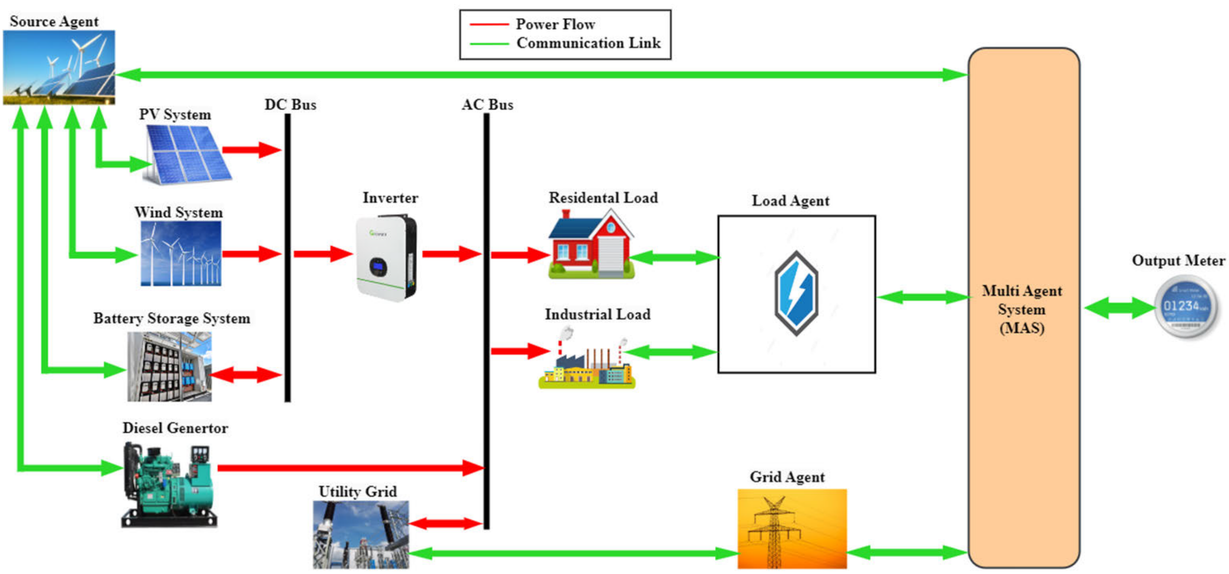
$CWind = (CW + OW)PWT$ (2)

where $CW$ = Cost per Watts; $OW$ = Operation & Maintenance Cost; $PWT$ = Power generated by the wind powersystem.

- **System**: Wind turbines connected to generators.
- **Cost Function**: CWind=(CW+OW)PWTC_{Wind} = (C_W + O_W) P_{WT}CWind=(CW+OW )PWT Where CWC_WCW is the cost per watt, OWO_WOW is the operation & maintenance cost, and PWTP_{WT}PWT is the power generated by the wind system.

*Diesel Generator*

- **Model**: Includes a synchronous machine, governor, and excitation system.




•Fuel Cost

$Cfuel = Cdiesel * FD$ (3)

where, *FD* =Amount of Fuel Consumed; *Cdiesel* =Price of diesel

• O&M Cost

*CO&M* = ρ∗*PD* ∗*dt* (4)

where, ρ = Operating cost (0.008 $/kWh); *PD* = Power generated by Diesel Generator; *dt* = Step

• Replacement Cost

*RDG* = *PDG*∗*NDG* ∗ (
1 + *fr*
1 + *ir*
) (5)

where, *PDG* = Price of Diesel Generator, *NDG* = Number of Diesel Generators, *fr* = inflation Rate, *ir* = Interest Rate

• Startup Cost

*Cstartup* =
_
σ*D* + δ*D*
_
1 − *e* − *TOFF*,*D*
*TD*
__
∗ (1 − *u*(*t*−1),*D*) (6)

*Battery Storage System (BSS)*

- **Model**: Lithium-ion battery connected to a bi-directional DC-DC buck-boost converter with a PID controller.
- **Operation**: Manages charging and discharging to balance supply and demand.

*Inverter*

- **Type**: Three-phase full-bridge inverter with six thyristors.
- **Function**: Converts DC power from PV and wind systems to AC power for the load.

*Utility Grid*

- **Specification**: 11 kV, used for purchasing or selling electricity.
- **Cost Function**: CGrid=CG×PGC_{Grid} = C_G \times P_GCGrid=CG×PG Where CGC_GCG is the price per unit offered by the grid, and PGP_GPG is the power from the utility grid.

*Objective Function*

- **Goal**: Minimize the energy cost of the microgrid.
- **Function**: Minimize ∑t=124(CPV+CWIND+CD+CGRID)\text{Minimize } \sum_{t=1}^{24}(C_{PV} + C_{WIND} + C_D + C_{GRID})Minimize t=1∑24(CPV+CWIND+CD+CGRID)

*MAS Strategy*

- **Agents**: Source, grid, and load agents, each managing respective components.
- **Control**: The MAS controller coordinates the performance and scheduling of agents based on local and collective information.

*PSO (Particle Swarm Optimization)*

- **Purpose**: Optimize power and cost functions by simulating particle movement and adjusting velocities to find the best solution.
- **Strategy**: Optimize the microgrid by adjusting parameters of PV, wind, diesel generator, BSS, and utility grid to minimize costs.

## III. SYSTEM ARCHITECTURE

Figure 2 illustrates the structure of the proposed microgrid system, incorporating PV, wind, diesel generators, and battery storage systems as primary energy sources. The system architecture is divided into three main components: the generation unit, storage unit, and load unit.

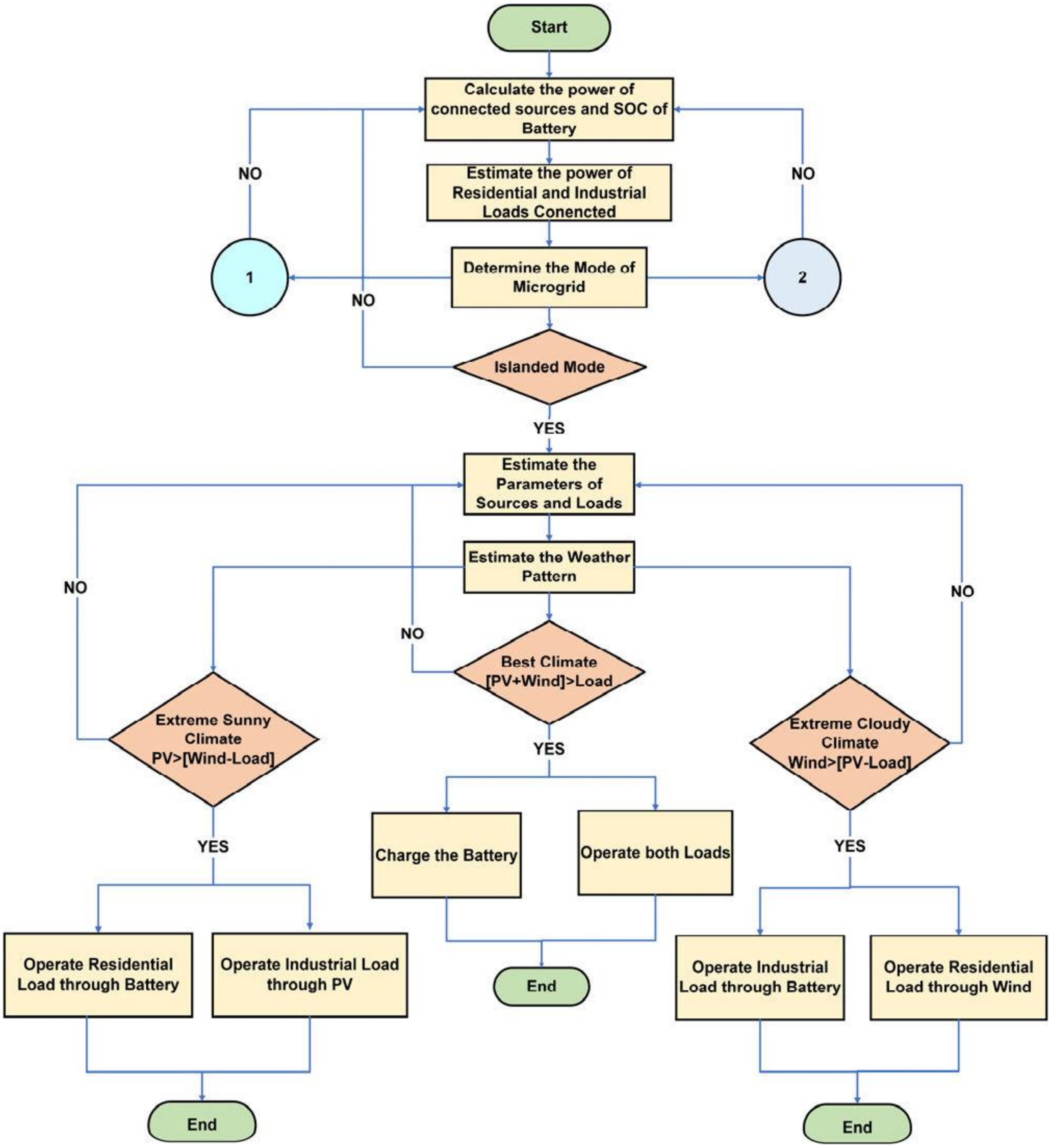



**FIGURE 2.** MAS Flowchart for Microgrid Operation and Control.

**A. Generation Unit**

The generation unit consists of PV, wind, and diesel generators, which supply power to the load. The power output from PV and wind is dependent on climatic conditions, while diesel generators provide backup power in case of insufficient RES.

**B. Storage Unit**

The storage unit comprises battery storage systems that store excess energy generated by RES and supply power to the load during low RES generation periods.

**C. Load Unit**

The load unit includes various types of loads, such as residential, commercial, and industrial, with different load profiles and energy demands.

## IV. OPERATIONAL MODES

The proposed hybrid microgrid operates in three distinct modes: islanded, transition to grid, and grid-oriented. Each mode is evaluated based on climatic scenarios to optimize resource allocation and achieve efficient energy management.

**A. Islanded Mode**

In islanded mode, the microgrid operates independently without connecting to the main grid. The system relies on RES and battery storage to supply power to the load. Climatic scenarios, such as the best, extreme sunny, extreme cloudy, and worst conditions, are considered for islanded mode operation.

**B. Transition to Grid Mode**

In transition to grid mode, the microgrid operates in a semi-autonomous state, where it can connect to the main grid when required. The system operates in sunny and cloudy scenarios to optimize power allocation during the transition phase.

**C. Grid-Oriented Mode**

In grid-oriented mode, the microgrid is fully connected to the main grid, allowing power exchange between the microgrid and the main grid. Grid-feed and grid-tied scenarios are considered for grid-oriented operation to achieve optimal energy management.

## V. OPTIMIZATION TECHNIQUE

As elucidated in the Figure 3, the PSO is implemented to optimize power allocation within the hybrid microgrid, enhancing its cost-effectiveness and energy management. The PSO algorithm optimizes the power generation and storage, considering the climatic scenarios and load demand to achieve optimal resource utilization.

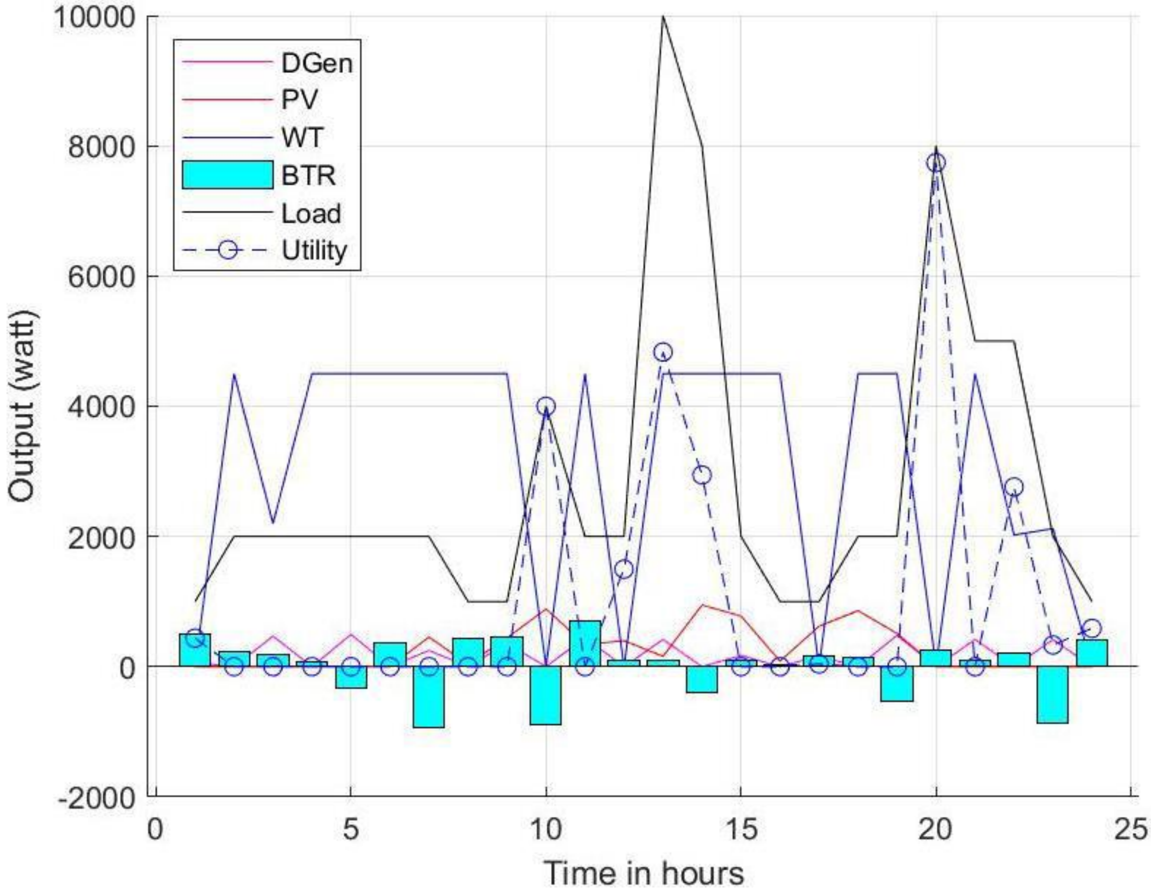



**FIGURE 3.** Optimized power curve schedule for 24 hours.

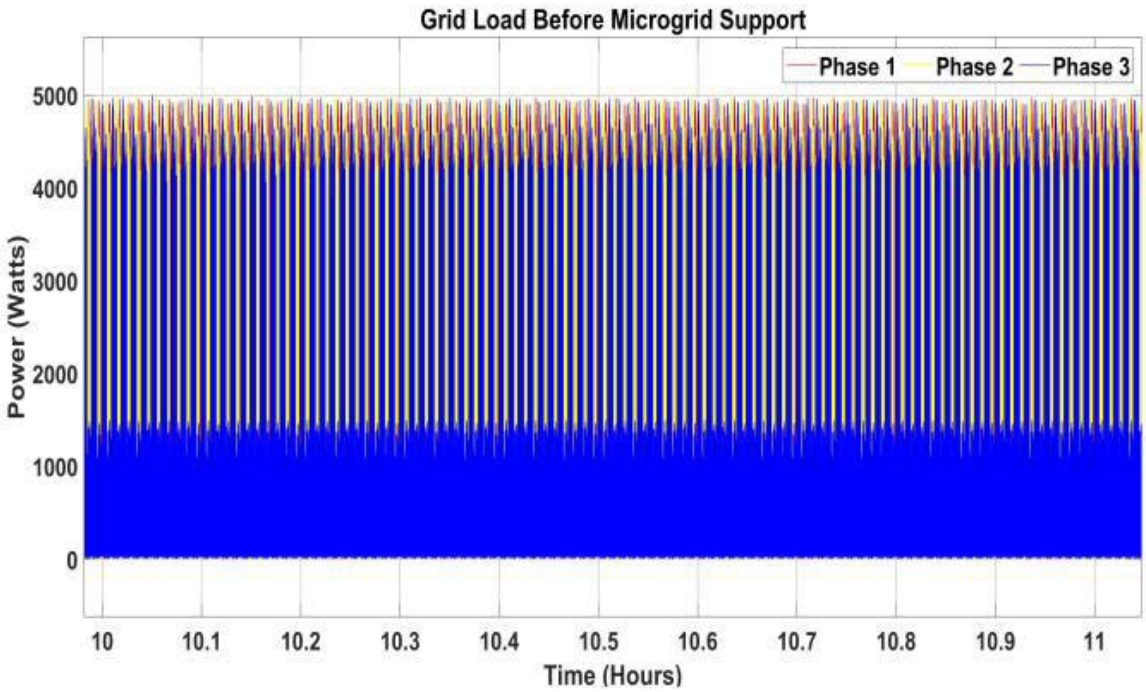



**FIGURE 4.** Grid Load before Microgrid Support

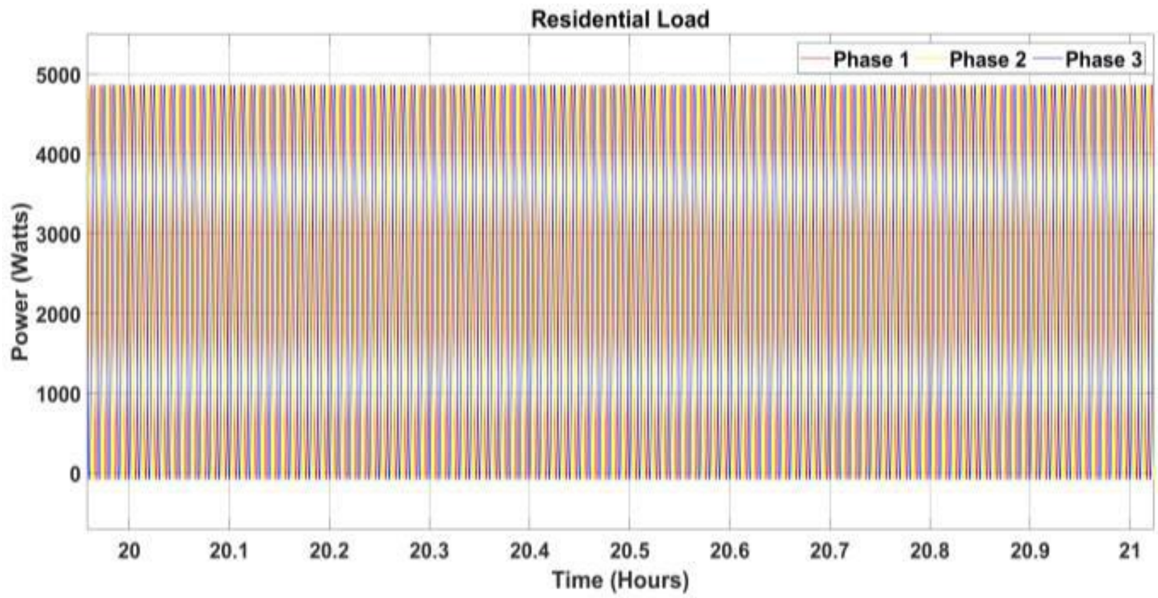



**FIGURE 5.** Residential load power (grid tied mode).

## VI. SIMULATION RESULTS

Simulation studies are performed using MATLAB/Simulink R2021a, evaluating the performance of the proposed hybrid microgrid in each operational mode. The results as seen in the figures 4-8, demonstrate efficient energy management, optimal resource allocation, and reduced environmental impacts using the MAS approach.

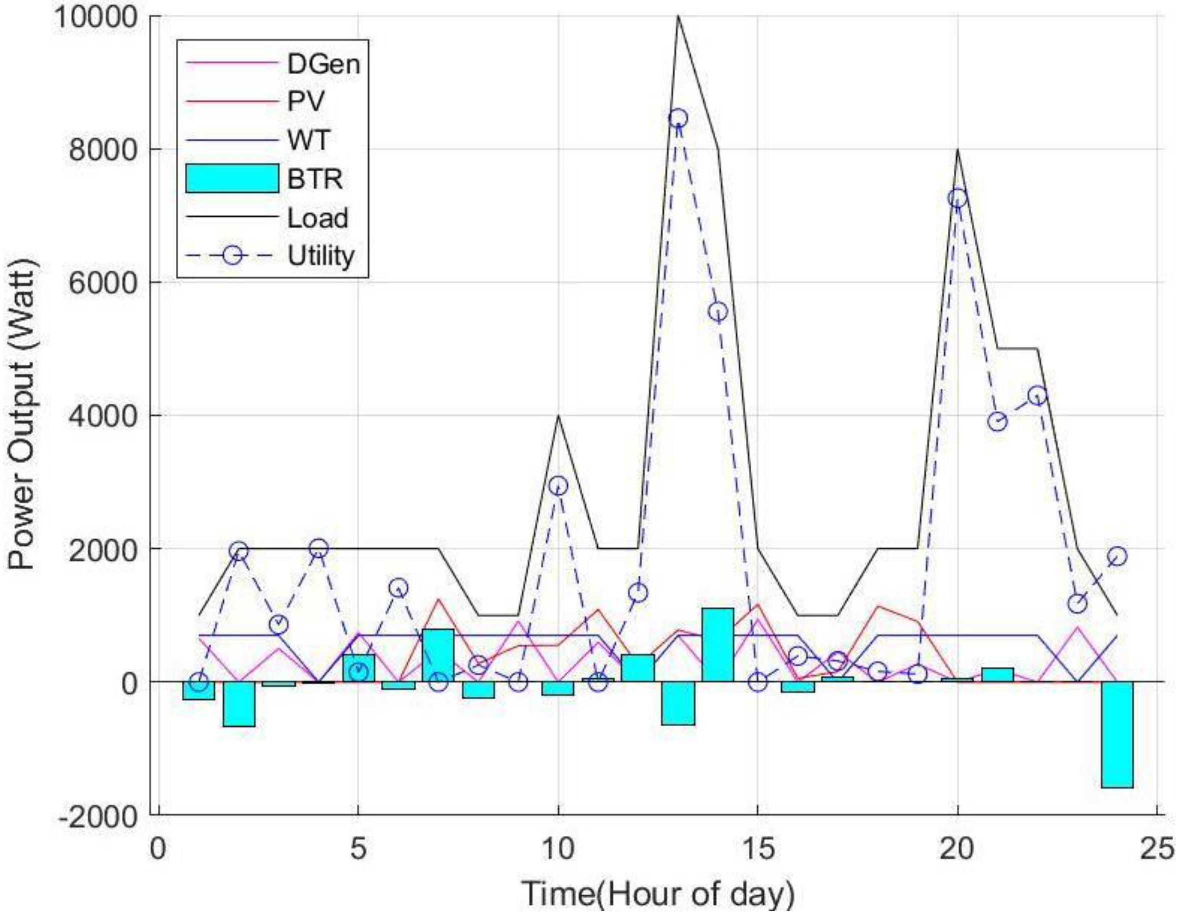



**FIGURE 6.** Optimized power curve schedule for 24 hours

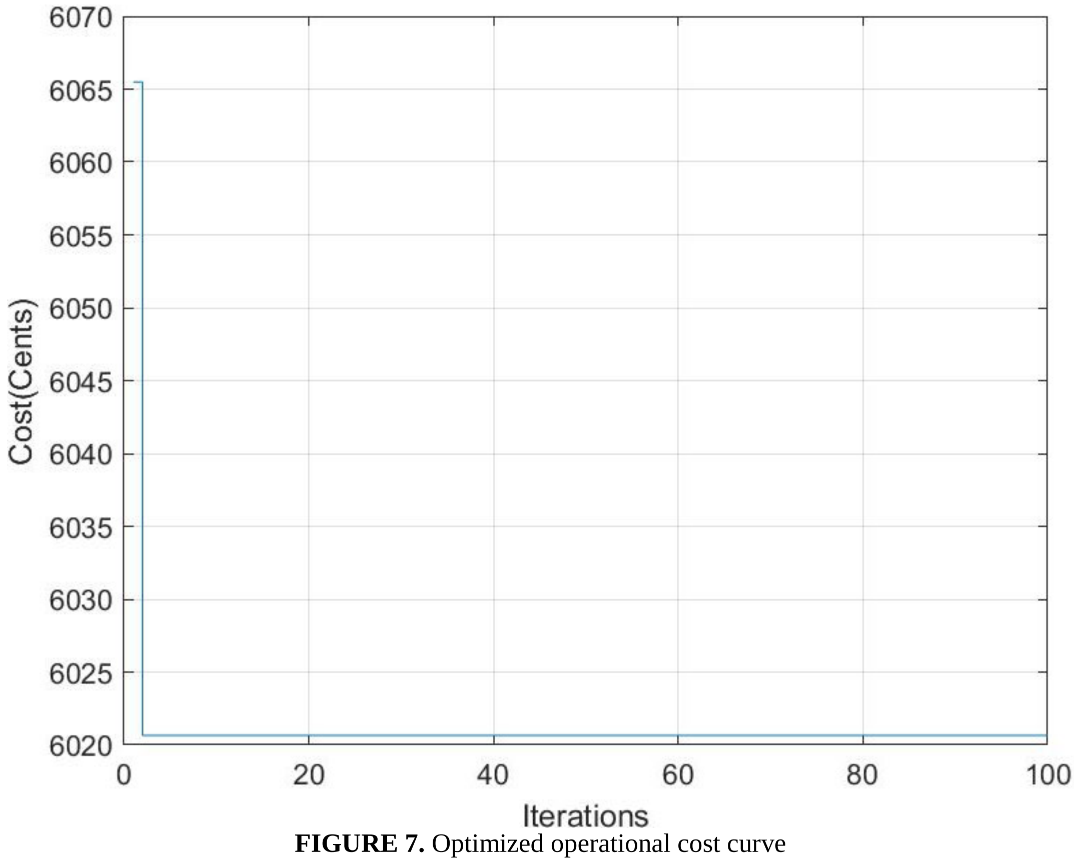



**FIGURE 7.** Optimized operational cost curve

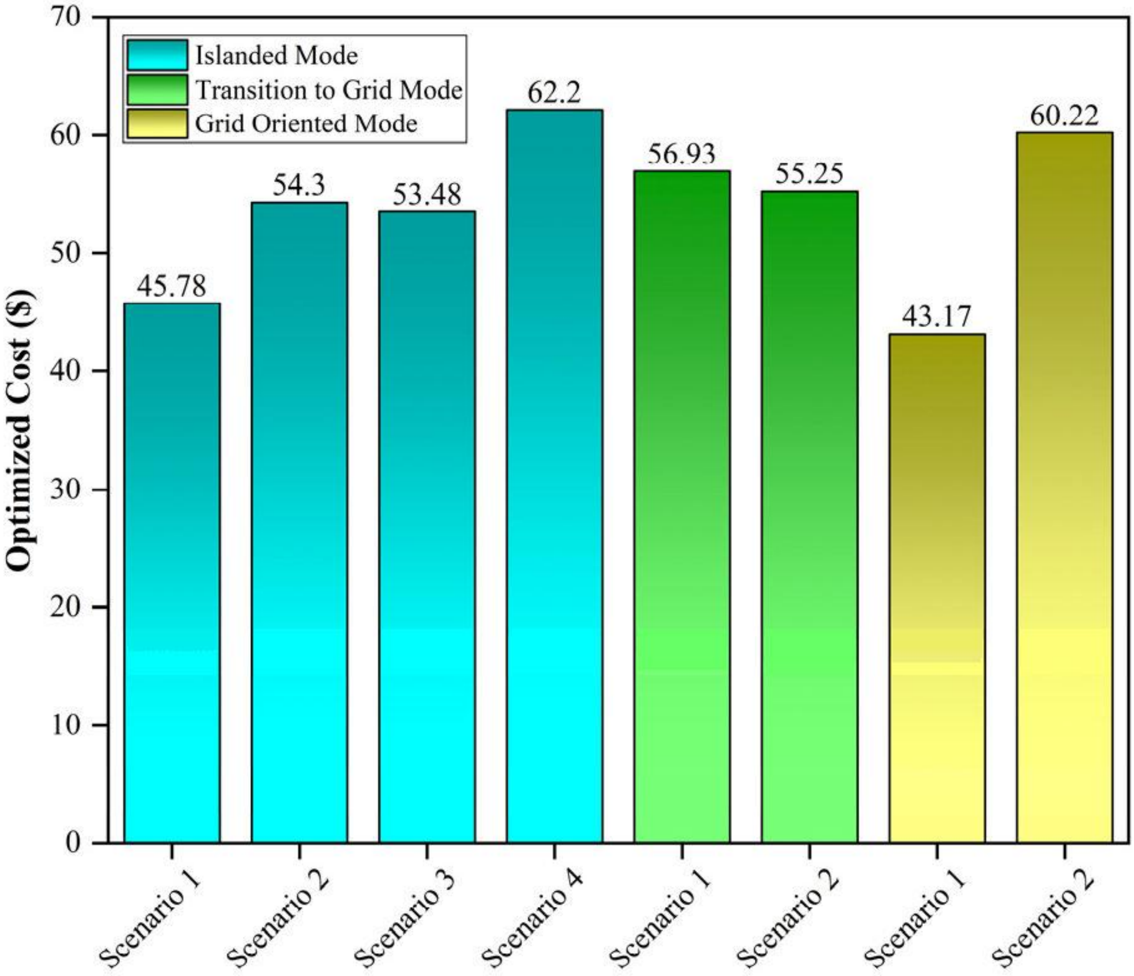



**FIGURE 8.** Optimized operational costs of microgrid scenarios

## VII. CONCLUSION

The study investigated the operational modes, resource optimization, and environmental impacts of MAS-based energy management in hybrid microgrids. Utilizing a Multi-Agent System (MAS) technique, the hybrid microgrid, incorporating Renewable Energy Sources (RES), a diesel generator, and a battery storage system, was managed under three distinct operational modes: islanded, transition to grid, and grid oriented. The performance optimization considered various climatic patterns, energy costs, source characteristics, and load demand. Simulation studies, conducted in the MATLAB/Simulink R2021a environment, demonstrated the system's capability to handle different climatic scenarios, including best, extreme sunny, extreme cloudy, and worst conditions for islanded mode; sunny and cloudy for transition to grid mode; and grid-feed and grid-tied for grid-oriented operation. Particle Swarm Optimization (PSO) was implemented to enhance power allocation and cost-effectiveness. The optimization results showcased efficient energy source utilization and effective energy management, affirming the significance of adopting a MAS approach for smart energy management in hybrid microgrids.

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