SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I1P102

Volume 12 Issue 1, 9-16, January 2025

Original Article

Smart Optimization for Environmental and Economic Dispatch with Renewable Energy Integration

K. Manikandan[1], P. Venkatesh[1*], B. Naga Pratyusha[2], K. Sarada[3], Arvind R. Singh[4]

[1]*Department of EEE, Dr. Mahalingam College of Engineering and Technology, Tamilnadu, India.*
[1*]*Department of Electrical and Electronics Engineering,*
Mohan Babu University (Erstwhile Sree Vidyanikethan Engineering College), Andhra Pradesh, India.
[2]*Department of EEE, Ballari Institute of Technology and Management, Indian Institute of Technology, Karnataka, India.*
[3]*Department of EEE, Koneru Lakshmaiah Education Foundation, Andhra Pradesh, India.*
[4]*Honorary Research Fellow, Applied Science Research Center, Applied Science Private University, Amman, Jordan.*

**Corresponding Author : venkateshp.engg@gmail.com*

Received: 01 November 2024 Revised: 03 December 2024 Accepted: 04 January 2025 Published: 25 January 2025

Abstract **-** *In recent years, the focus on optimal scheduling methods for Microgrids (MGs) has intensified due to their ability to efficiently manage Distributed Generation (DG) over varying time intervals. The intermittent nature of renewable energy sources like wind and solar creates significant challenges for economic dispatch within MGs, as their unpredictability complicates coordination among energy sources. This paper presents a novel, comprehensive framework for multi-objective optimal dispatch in MGs, considering both ecological and economic factors. The framework integrates various generating units, including Photovoltaic (PV) systems, Wind Turbines (WT), Microturbines (MT), Fuel Cells (FC), and Battery Storage (BT) systems. To address the complexities of balancing multiple objectives and the stochastic nature of renewable energy, the research aims to develop a feasible multi-objective optimal dispatch strategy that improves MG operations by making them faster, more stable, and more efficient in convergence. Advanced optimization techniques, particularly intelligent algorithms, are utilized within a robust simulation environment to tackle the challenges. The study develops and partially tests a mathematical model for multi-objective optimal dispatch, facilitating dynamic parameter calculations to ensure efficient system operations despite renewable energy complexities. This research demonstrates the potential for a highly efficient, sustainable MG dispatch system using intelligent optimization, providing insights for future experimental implementations and refinements.*

Keywords **-** *Distributed generations, Fuel cells, Microgrid, Photovoltaic cells.*

1. Introduction

The economic dispatch problem in electrical power generation is intended to determine the optimal output level of active generating units to satisfy the required demand while respecting the system's limitations. Microgrids (MGs) provide practical approaches to diverse power system difficulties by incorporating both conventional and sustainable energy sources, such as Combined Heat and Power (CHP) facilities and Distributed Energy Resources (DER). This is accomplished by optimizing the layout of the power grid and integrating demand response from the load side into the conventional economic dispatch model for power generation. Various sub-goals with varying degrees of priority are proposed to adequately capture the multifarious aspects of monetary outlay, ecological considerations, and the reliability of the power supply. Reducing operating costs is essential for achieving cost-effective microgrid distribution. Power equilibrium equation limitations, component operation procedure constraints, energy storage constraints, and thermal energy storage constraints are all accounted for in the analysis. Economic dispatch and voltage regulation are simultaneously attained through a dual-tier control strategy. There is a lot of variation in the effectiveness of dispatching due to the temporal dynamics of reaction times across various load-side dispatching resources. As a result, there is an opportunity to maximize benefits from both the generation and load sides through the strategic deployment of dispatching mechanisms. A large range of different operation combinations can be used to carry out the algorithm. A distribution network's key component is efficient and impregnable dispatching that supports its operational framework. The issue at hand is the ecologically constrained economic dispatch dilemma, which is both complicated and intricate. To solve this problem, we must optimize numerous nonlinear objectives within a set of restrictions. Designing a thorough system that successfully harmonizes the complex interplay between emissions and energy costs is critical. Many approaches are taken to address the difficulties of emissions and economic dispatch. To solve this problem, we factored in a wide range of potential price increases. Microgrids are small-scale electrical networks used to power residential areas with low energy demand. They can provide customers various benefits like increased dependability, cost savings, lower carbon footprints, and renewable energy sources. Microgrids can potentially reduce environmental impacts caused by conventional, centralized power generation while simultaneously promoting and integrating Renewable Energy Sources (RES). Xiaoyan Ma et al. (2022) examined costs related to carbon emissions, system management, equipment depreciation, microgrid integration, and time-of-use tariffs, highlighting the environmental benefits of renewable energy. S. Vasanthakumar et al. (2015) discussed how micro-energy grids optimize energy use by integrating cooling, heating, and power generation technologies.

Manzoor Ellahi et al. (2020) highlighted the unpredictability of power output in microgrids, which poses safety and stability challenges for effective energy management. Xiaotong Song et al. (2020) demonstrated a method to simplify multi-objective economic emission dispatch problems into single-objective issues using price penalty factors. Siddharth Singh et al. (2020) addressed the multi-objective, nonlinear economic dispatch problem under environmental constraints, proposing various strategies involving Price Penalty Factors (PPF) to balance generation costs and emissions. Donglei Sun et al. (2020) proposed an approach to address energy systems' operational, economic, and environmental issues through multi-objective optimization strategies like economic dispatch [1-6]. Mokhtar Said et al. (2022) have analyzed an algorithm for Integrating RESs into the electricity grid. This complex task must be accomplished to minimize toxic gas emissions and reduce heat transfer costs. This complex procedure needs to be carried out within the framework of the system's many restrictions. Each of the aforesaid algorithms uses a two-stage search strategy to find the best solution in a given search space. Their sole methodological interest is in population growth and change. An extensive search on a worldwide and national scale. Hourly granular meteorological data is used pragmatically to achieve dynamic coordination between conventional power plants and Renewable Energy Sources (RESs) [7]. Using a consensus algorithm, Liu et al. present a novel, completely distributed economic dispatch technique for DC microgrids. Their method provides decentralized control, improving the efficiency and stability of the grid. This study represents a major development in decentralized energy optimization techniques and microgrid management [8]. Muhammad Waleed Tahir et al. (2022) have presented an innovative strategy for efficient energy use. Economic emissions and Energy Scheduling within a network rich in renewable resources were at the heart of their concept. This cutting-edge architecture was motivated by natural optimization mechanisms seen in biology [9]. A thorough examination of the relevant literature reveals the ability to use a unique bio-inspired algorithm to efficiently solve the complex task of the EED problem while simultaneously integrating renewable energy sources. P. Venkatesh et al. (2023) have demonstrated the algorithm for Allocating and administering the combined economic emission burdens effectively using machine learning algorithms [10]. Chao-Hsien Hsiao et al. (2021) have proposed a new technique for economically disposing of microgrids. Particle swarm optimization and the binning technique are at the heart of this approach [11]. Kanchan Pawani et al. (2021) have illustrated a new method for solving the Economic Load Dispatch problem using the Black Widow Optimization algorithm. [12] Qing Wang et al. (2019) have proposed a method that uses scenario analysis to enable the dynamic economic power dispatch of microgrids. Renewable energy has the potential to alleviate the current energy problem, but its incorporation into the grid infrastructure increases the inherent unpredictability of this type of energy. Microgrids have made great strides in reducing the strain on the traditional electrical grid from renewable energy sources [13]. Paramguru et al. (2021), The Emperor Penguin Optimization Algorithm is used to integrate microgrids with wind energy in order to solve the Economic Dispatch Problem. Their approach maximizes power generation, improving the grid's efficiency and using renewable energy sources. This study advances solutions for sustainable energy management in power systems [14]. Zhu et al. (2020) have used a comprehensive typical scenario set to offer a stochastic economic dispatching technique for active distribution networks. Their method increases grid efficiency and resilience by introducing uncertainty. This research offers a useful approach for maximizing power distribution in dynamic and unpredictable contexts [15].

Venkatesh and Visali suggest using machine learning and soft computing techniques to improve power system security. Through the utilization of these sophisticated techniques, they provide creative approaches to risk reduction and reliable power supply. This research significantly contributes to protecting power systems from possible threats and disturbances [16]. Swief, El-Amary, and Kamh (2020) have presented a comprehensive approach to energy management to address uncertainty in load and renewables integration for plug-in hybrid vehicles. Their creative strategy promises increased dependability and sustainability, which makes it a noteworthy addition to the fields of energy optimization and environmentally friendly transportation [17, 18]. Das, Mukherjee, and Das (2020) have introduced the "Student Psychology Based Optimization Algorithm". This innovative method uses concepts from student psychology to solve optimization issues. The approach, described in Advances in Engineering Software, has a novel population-based strategy that shows promise for effective problem-solving[19]. This creative strategy maximizes electricity production from renewable sources while integrating environmental restrictions with economic dispatch. It maximizes effectiveness while minimizing environmental impact by considering variables like emissions limitations and the availability of renewable energy. With environmental concerns mounting, this development is a big step toward sustainable energy management.

2. Problem Formation

Objective Function: This function aims to reduce overall generation costs and emissions for each Distributed Generation (DG) unit.

$$\text{Min } \mathrm{K}(P_i) = \sum_{j=1}^{n} C_{g,j}(P_j) + \sum_{j=1}^{n} C_{e,j}(P_j) \quad (1)$$

In the MG system, ‘n’ is the number of DG units. K(Pj) is the total operating cost ($/hr) of these units. Cg,j is the generation cost, Ce,j is the emission cost, and Pj is the power output of the jth DG unit.

2.1. Operating and Maintenance Costs

2.1.1. Fuel Cost (FC)

$$D_f(P_\mathrm{j}) = \mathrm{K}_{\mathrm{f,j}} \times \mathrm{P}_j \quad (2)$$

Where Pj is the output power produced by the jth DG unit, Kf,j is the fuel coefficient of the jth DG unit/kWh, and D(f,j) (Pj) is the FC of the jth DG unit/h.

2.1.2. Operating Cost

$$Y_{\mathrm{o,j}}(P_\mathrm{j}) = \mathrm{K}_{\mathrm{o,j}} \times \mathrm{P}_j \quad (3)$$

Where Pj is the output power produced by the jth DG unit, Yo,j(Pj) is the operation and maintenance cost of the jth DG unit, and Ko,j is the operation and maintenance coefficient ($/kWh).

2.1.3. Emission Cost

$$Q_{\mathrm{e,i}}(P_\mathrm{i}) = \mathrm{K}_{\mathrm{o,i}} \times \mathrm{M}_e \times \mathrm{P}_i \quad (4)$$

K(e,j) represents the emissions coefficient for the jth Distributed Generation (DG) unit per kilowatt-hour (kWh), and Qe,j(Pj) denote the emission cost for the jth DG unit per kWh. The variable I stands for the price of greenhouse gas emissions per kilogram, while Pj refers to the power output of the j^{th} DG unit.

2.2. Constraints

2.2.1. Power Balance Constraint

$$P_D = \sum_{\mathrm{ni}=1} P_i + P_B \quad (5)$$

Where, Pi =Active power generation of DG unit, PD = total demand, and PB = capacity of battery.

2.2.2. DG Output Limits

$$Pi_{i,max_{i,min}} \quad (6)$$

where Pi, min, Pi, and max represent the DG unit’s lower and higher power limits, respectively.

2.2.3. The Operational Limitations Pertaining to the Battery

$$-PB_{max_{B_{min}}} \quad (7)$$

PBmax represents the pinnacle of the battery’s charging potential, while -PBmax signifies the utmost capacity for discharging power.

3. Student Psychology-Based Optimization (SPBO)

SPBO Students aim to be at the top of their class by performing exceptionally well on their final exams. Examination scores are used to evaluate performance.

A student is considered to be at the top of their class if they score the highest on the final exam. If you want to be the top student in your class, you need to work harder than the rest of your classmates to raise your exam scores on each topic.

If they wish to be recognized as the best of their class, pupils must excel above their peers. To succeed, they must put in more effort to master the material. They need to do well across the board to improve their final grade.

Therefore, students should make an effort in each subject if they want to improve in general. However, a student’s ability, productivity, and excitement for a given subject affect how much effort they are willing to put in. It is, therefore, essential to stress that not all students may experience the same level of improvement in their exam results. Student effort depends on their personalities.

Some pupils aspire to outwork the best. Some of my classmates strive, but they also try to beat the smart kids and the best students.

Academic progress depends on effort. Students concentrate harder in subjects they love to improve their exam scores. The algorithm working procedure and mathematical analysis of student psychology were referred to and analyzed [19]. SPBO is shown in Figure 1.

4. Simulation Results and Discussion

A study that optimized the economic and ecological dispatch of a Microgrid (MG) using the Stochastic Particle Swarm Optimisation (SPBO) method is shown here. SPBO results are compared to Lagrange outcomes to determine efficacy. SPBO is best for environmental and economic dispatch. Daily MG system requirements.

The recommended Stochastic Parallel Branch and Optimization (SPBO) approach reduced the microgrid’s economic power dispatch challenge’s economic and emission costs. Six solar-wind generators cost the following.

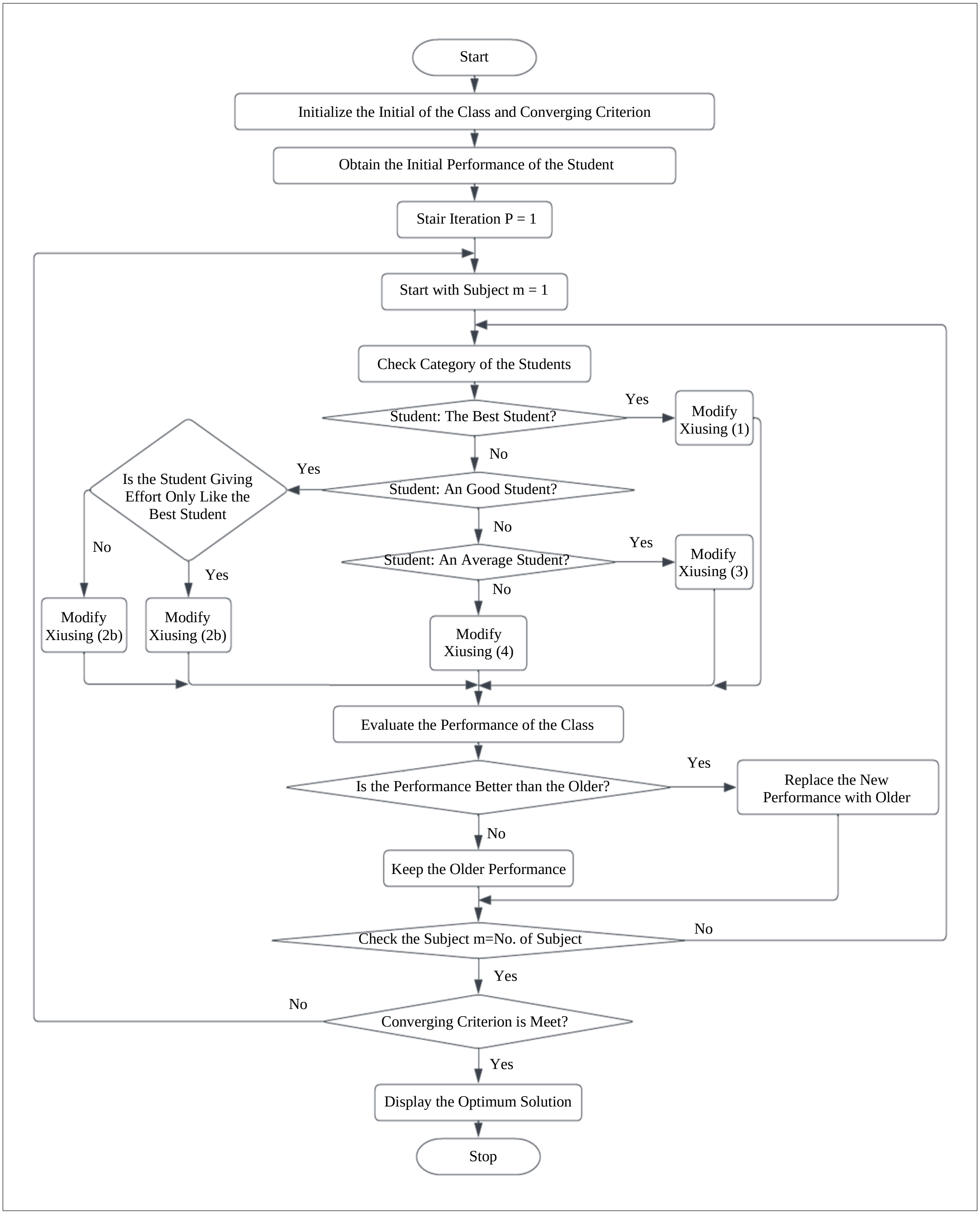

Fig. 1 Flowchart for SPBO

4.1. Case 1: Six Generating Units

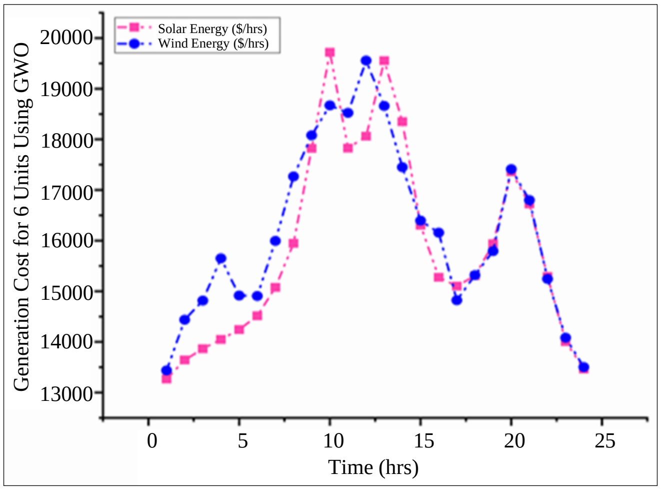

Fig. 2 Generation cost for 6 units using solar and wind energy with the GWO method

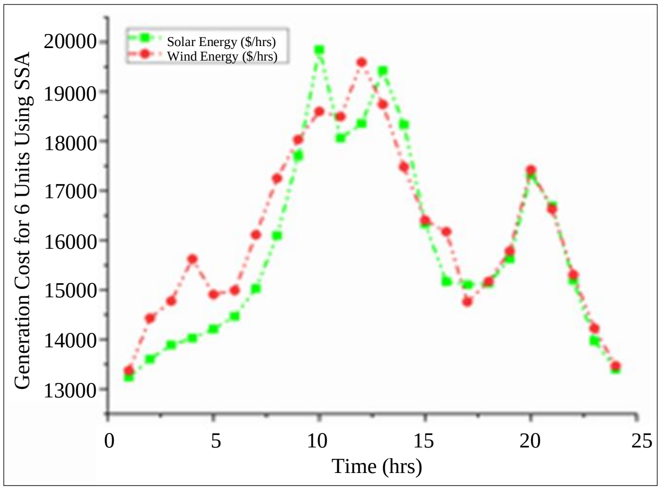

Fig. 3 Generation cost for 6 units using solar and wind energy with the SSA method

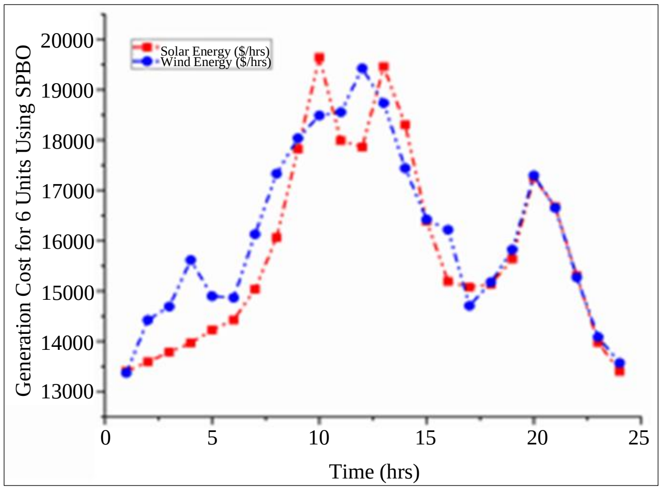

Fig. 4. Generation cost for 6 units using solar and wind energy with the SPBO method

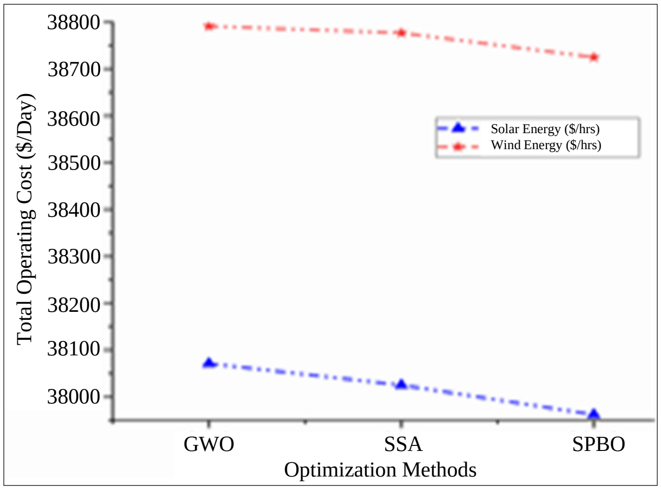

Fig. 5 The total operating cost for 6 units using solar and wind energy with the SPBO method

Table 1. Generation cost and total operation cost comparison using GWO, SSA, and SPBO for 6 generating units without RES and with RES for 24-hour demand

Time	Without RES			With RES		
	GO	SSA	SPBO	GO	SSA	SPBO
1	13334	13212	13216	13373	13388	13370
2	13600	13710	13597	14435	14478	14433
3	13811	13809	13876	14711	14743	14691
4	14138	13995	14100	15635	15700	15645
5	14199	14203	14258	14964	15028	14976
6	14414	14475	14535	14976	14872	14860
7	14649	14666	14642	16519	16569	16459
8	14870	14935	14816	18440	18407	18413
9	16043	16422	16230	19722	19640	19671
10	16900	17009	16809	21323	21366	21276

11	17431	17330	17327	19104	19063	18959
12	17878	17723	17736	19764	19705	19786
13	17543	17503	17312	20824	20797	20784
14	16675	16614	16628	19399	19266	19300
15	15668	15687	15712	17177	17163	17113
16	14842	14844	14826	16543	16509	16595
17	14398	14373	14442	15503	15498	15414
18	14972	15172	15058	15371	15440	15470
19	15739	15696	15675	15698	15692	15759
20	17501	17290	17242	17548	17284	17328
21	16700	16653	16762	16639	16637	16590
22	15294	15217	15220	15239	15258	15245
23	14015	14006	14002	14099	14098	14161
24	13516	13401	13406	13470	13506	13514

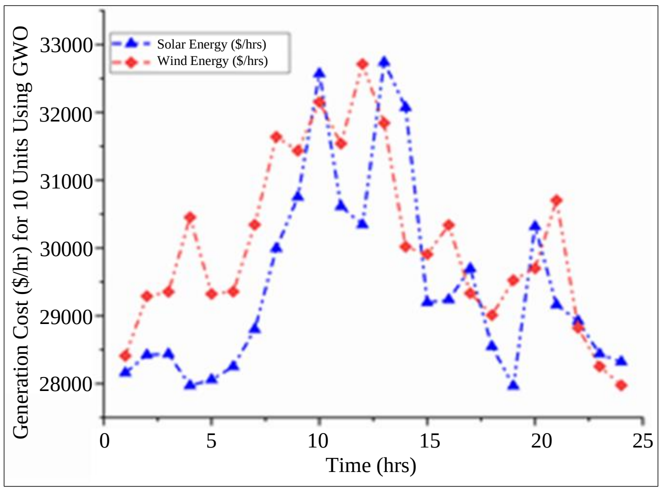

Fig. 6 Generation cost for 10 units with solar and wind energy using the GWO method

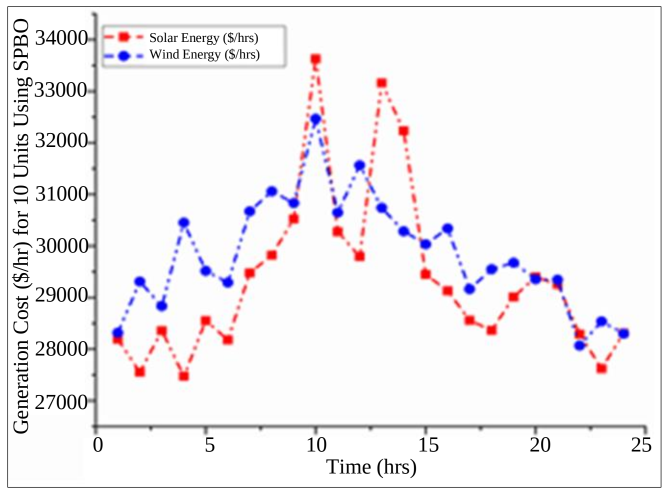

Fig. 8 Generation cost for 10 units with solar and wind energy using the SPBO method

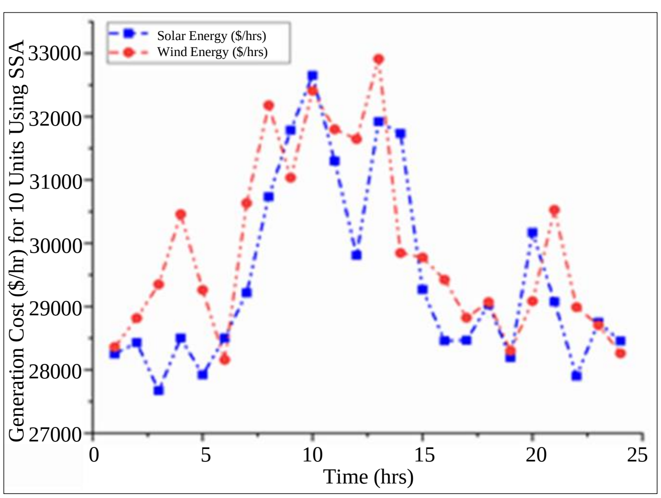

Fig. 7 Generation cost for 10 units with solar and wind energy using the SSA method

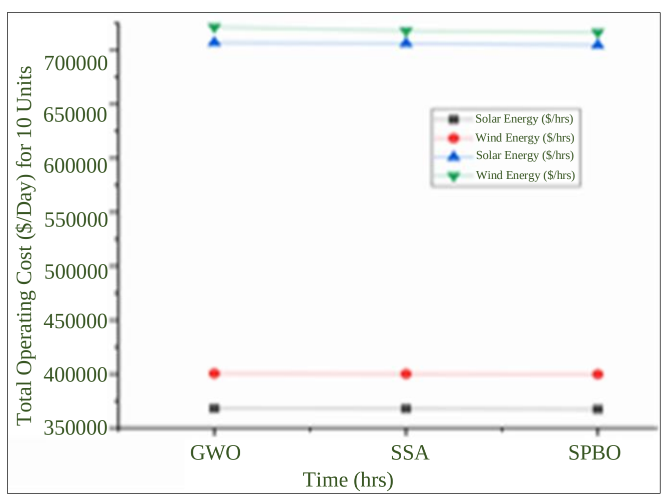

Fig. 9 The total operating cost for 10 units using renewable energies with optimization methods for 24-hour demand

Table 2. Comparative analysis of optimization techniques for generation cost and total operation cost of 10 generating units with and without RES for 24-hour demand

Time	Without RES			With RES		
	GWO	SSA	SPBO	GWO	SSA	SPBO
1	27984	28184	27880	28308	28441	28099
2	28345	27626	28302	29226	29148	28840
3	28598	28449	28628	29432	29557	29511
4	28689	27706	27929	30496	30414	29888
5	28817	28761	27437	29443	29523	29475
6	27660	28883	28625	29158	29379	28321
7	28583	28468	27975	30890	31079	31153
8	29004	28592	29129	33250	33422	33365
9	29302	29260	28416	33847	34220	34031
10	30745	30272	29010	35182	35558	34995
11	30846	30748	29164	31834	31225	31567
12	30398	30545	29940	31746	33107	31932
13	29966	30185	30431	34636	33595	34725
14	28819	28989	29520	32654	32853	32791
15	28907	29012	28395	31007	30469	30032
16	28603	28579	29388	30988	30440	30023
17	27803	28117	27691	29916	29766	30083
18	29154	28696	28281	29117	29738	29233
19	29586	29307	29247	29187	28306	28643
20	31079	29236	30572	30639	29968	31031
21	30451	29019	29196	29244	29266	28884
22	28441	29313	27990	29264	28711	28276
23	28342	28453	28699	28062	28602	27953
24	28333	28277	28203	28395	28328	28250

4.2. Case 2: Ten Generating Units

Figures 6 to 8 explain the individual solar energy and wind energy utilized to support the 10 generating units by using optimization algorithms (i.e., GWO, SSA, and SPBO) for 24-hour demand.

5. Conclusion

Using the Price Penalty Factor (PPF), the Grey Wolf Optimization (GWO), the Sparrow Search Algorithm (SSA), and the Student Psychology Based Optimization (SPBO) have all been used to solve the Combined Economic and Emission Dispatch (CEED) problem for a 24-hour demand. By conducting a comprehensive analysis of the total cost associated with various methods for meeting 24-hour demand. This paper will use the GWO, SSA, and SPBO algorithms to address the CEED problem by implementing the price penalty factor.

The price penalty factor for the min/max approach has proven to yield optimal outcomes when successfully resolving the CEED problem. The outcome derived from the SPBO shall be juxtaposed with the GWO and SSA for comprehensive analysis and evaluation. The proposed SPBO method demonstrates superior performance in optimizing the total fuel cost for the CEED problem, surpassing both GWO and SSA. Henceforth, the proposed Strategic Performance Boosting Optimization (SPBO) solution yields superior outcomes and adeptly resolves the intricate Combined Economic and Emission Dispatch Problem. In further work, valve point load effects, uncertain constraints, and energy storage devices can be incorporated into analyzing the optimal allocation of generators.

Nomenclature

$K(P_i)$	Total operating cost ($/hrs)
$C_{g,j}$	Cost of generation (kW)
$C_{e,j}$	Cost of Emission
P_j	Power output produced at the j^{th} bus(kW)
$K_{f,j}$	Fuel coefficient of the jth DG unit/kWh
$Y_{o,j}(P_j)$	operation and maintenance cost of the j^{th} DG unit
$K_{o,j}$	Operation and Maintenance coefficient ($/kWh)
$K_{e,j}$	Emissions coefficient at jth DG unit/kWh
$Q_{e,j}(P_j)$	Emission cost of the j^{th} DG unit/kWh
X_{best}	best student mark obtained
X_j	Randomly selected J^{th} student
T_{amb}	Ambient temperature (°C or K)
V_{oc}	Open-circuit voltage (V)
ELD	Economic Load Dispatch

ED	Emission Dispatch		GWO	Gray Wolf Optimization
EED	Economic and Emission Dispatch		SSA	Sparrow Search Algorithm
DER	Distributed Energy Resources		SPBO	Student Psychology based optimization

References

[1] Xiaoyan Ma et al., "Multi-Objective Microgrid Optimal Dispatching Based on Improved Bird Swarm Algorithm," Global Energy Interconnection, vol. 5, no. 2, pp. 154-167, 2022. [CrossRef] [Google Scholar] [Publisher link]

[2] Arvind R. Singh et al., "Design and Performance Evaluation of A Multi-Load and Multi-Source DC-DC Converter for Efficient Electric Vehicle Power Systems," *Scientific Reports*, vol. 14, no. 1, 2024. [CrossRef] [Google Scholar] [Publisher link]

[3] Manzoor Ellahi, and Ghulam Abbas, "A Hybrid Metaheuristic Approach for the Solution of Renewables-Incorporated Economic Dispatch Problems," *IEEE Access*, vol. 8, pp. 127608-127621, 2020. [CrossRef] [Google Scholar] [Publisher link]

[4] K. Suresh et al., "Design and Implementation of A Universal Converter for Microgrid Applications Using Approximate Dynamic Programming and Artificial Neural Networks," *Scientific Reports*, vol. 14, no. 1, 2024. [CrossRef] [Google Scholar] [Publisher link]

[5] Siddharat Singh, and Ashwani Kumar, "Economic Dispatch for Multi Heat-Electric Energy Source Based Microgrid," *In Proceedings 2020 IEEE 9th Power India International Conference (PIICON)*, Sonepat, India, 2020. [CrossRef] [Google Scholar] [Publisher link]

[6] Donglei Sun et al., "Integrated Generation-Grid-Load Economic Dispatch considering Demand Response," *In Proceedings 2020 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia)*, Weihai, China, 2020. [CrossRef] [Google Scholar] [Publisher link]

[7] Mokhtar Said et al., "Economic Load Dispatch Problem Based on Search and Rescue Optimization Algorithm," *IEEE Access*, vol. 10, pp. 47109-47122, 2022. [CrossRef] [Google Scholar] [Publisher link]

[8] Dan Liu et al., "A Fully Distributed Economic Dispatch Method in DC Microgrid Based on Consensus Algorithm," *IEEE Access*, vol. 10, pp. 119345-119356, 2022. [CrossRef] [Google Scholar] [Publisher link]

[9] Muhammad Waleed Tahir et al., "Economic Emission and Energy Scheduling for Renewable Rich Network Using Bio-Inspired Optimization," *IEEE Access*, vol. 10, pp. 79713-79729, 2022. [CrossRef] [Google Scholar] [Publisher link]

[10] E. Parimalasundar et al., "Single-Phase Modular Multilevel Inverter with Controlled DC-Cells for Renewable Energy Applications,," *2024 10th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, pp. 1-6, 2024. [CrossRef] [Google Scholar] [Publisher link]

[11] Chao-Hsien Hsiao et al., "Economic Dispatch of Microgrids Using Particle Swarm Optimization and Binning Method," *In Proceedings 2021 IEEE International Future Energy Electronics Conference (IFEEC)*, Taipei, Taiwan, 2022. [CrossRef] [Google Scholar] [Publisher link]

[12] E. Parimalasundar et al., "Investigation Analysis of Open Circuit and Short Circuit Fault on Cascaded H-Bridged Multilevel Inverter Using Artificial Neural Network Approach," *International Journal of Electrical and Electronics Research*, vol. 10, no. 2, 320-326, 2022. [CrossRef] [Google Scholar] [Publisher link]

[13] Qing Wang et al., "Dynamic Economic Dispatch of Micro-Grid Based on Scenario Analysis," *In Proceedings 2019 IEEE Sustainable Power and Energy Conference (iSPEC)*, Beijing, China, 2020. [CrossRef] [Google Scholar] [Publisher link]

[14] K. Suresh and E. Parimalasundar, "IPWM Based IBMSC DC-AC Converter Using Solar Power for Wide Voltage Conversion System," *IEEE Canadian Journal of Electrical and Computer Engineering*, vol. 45, no. 4, pp. 394-400, 2022. [CrossRef] [Google Scholar] [Publisher link]

[15] Huimin Zhu, Shun Yuan, and Chunlai Li, "Stochastic Economic Dispatching Strategy of the Active Distribution Network Based on Comprehensive Typical Scenario Set," *IEEE Access*, vol. 8, pp. 201147-201157, 2020. [CrossRef] [Google Scholar] [Publisher link]

[16] Busireddy Hemanth Kumar et al., "A High Gain Switched Capacitor – Inductor DC-DC Converter for a RES Applications," *2024 10th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, pp. 1-5, 2024. [CrossRef] [Google Scholar] [Publisher link]

[17] Rania A. Swief, Noha H. El-Amary, and Mohamed Zakaria Kamh, Optimal Energy Management Integrating Plug-in Hybrid Vehicle Under Load and Renewable Uncertainties," *IEEE Access*, vol. 8, pp. 176895-176904, 2020. [CrossRef] [Google Scholar] [Publisher link]

[18] Yang Gao, and Qian Ai, "Demand-side Response Strategy of Multi-Microgrids Based on an Improved Co-evolution Algorithm," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 45-52, 2021. [CrossRef] [Google Scholar] [Publisher link]

[19] Bikash Das, V. Mukherjee, and Debapriya Das, "Student Psychology-Based Optimization Algorithm: A New Population-Based Optimization Algorithm for Solving Optimization Problems," Advances in Engineering Software vol. 146, 2021. [CrossRef] [Google Scholar] [Publisher link]