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Economic Dispatch and Optimization of Renewable-Rich Power System: A Critical Review of Classical and Metaheuristic Approaches

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ABSTRACT

The increasing integration of renewable energy sources into modern power systems has significantly changed the economic dispatch problem, creating new challenges associated with variability, uncertainty, nonlinearity, operational constraints, and the need for reliable and economic power-system operation. This review critically examines economic dispatch and optimization techniques applicable to renewable-rich power systems, with particular emphasis on classical and meta-heuristic approaches. The review synthesizes studies covering conventional optimization techniques, particle swarm optimization, genetic algorithms, Grey Wolf Optimization, Jaya, Bat Algorithm, African Vulture Optimization, One-to-One Optimization, hybrid algorithms, and other emerging intelligent optimization methods. Classical techniques provide computationally efficient solutions for relatively simple and convex dispatch problems; however, their effectiveness can be reduced when nonlinear characteristics, renewable uncertainty, multiple objectives, and complex operational constraints are introduced. The reviewed studies also indicate increasing interest in hybrid methods that combine the strengths of different optimization techniques. However, important limitations remain, including insufficient consideration of renewable-generation uncertainty, limited integration of energy storage and demand response, restricted treatment of network security and transmission constraints, scalability issues, and inadequate validation using large-scale or real-world power systems. The review therefore identifies a continuing need for adaptive, robust, and computationally efficient optimization frameworks capable of simultaneously addressing economic, environmental, and operational requirements. Overall, the review provides a structured understanding of the development of economic dispatch methods and highlights research directions for achieving reliable, flexible, and sustainable operation of renewable-rich power systems.

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INTRODUCTION

The continuous growth in electricity demand and the increasing penetration of renewable energy sources have significantly transformed the operation and planning of modern power systems. Renewable technologies such as solar photovoltaic (PV) and wind power provide important opportunities for reducing dependence on conventional fossil-fuel generation and improving the sustainability of electricity supply. However, their variable and uncertain nature introduces additional operational challenges because renewable generation does not remain constant over time. Consequently, power-system operators require effective optimization techniques capable of coordinating conventional

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generators, renewable resources, storage technologies, and other flexible resources while maintaining an economical and reliable supply of electricity [1], [2],[3]. Studies in the reviewed literature show that economic dispatch has consequently evolved from a relatively conventional cost-minimization problem into a more complex optimization problem involving multiple objectives and operational constraints.

Economic dispatch (ED) is fundamentally concerned with determining the appropriate output of available generating units so that the required electrical demand is satisfied at minimum operating cost while respecting generator and network constraints. Traditional ED approaches are generally based on mathematical optimization techniques and are particularly effective when the objective and constraints have relatively simple and well-defined characteristics. Classical approaches, including linear programming (LP), quadratic programming (QP), and lambda-iteration-based techniques, have therefore remained important tools for solving dispatch problems. A 2024 review of optimization techniques for distributed generation identified classical methods as important approaches for satisfying power-demand and network constraints while minimizing generation costs, while also noting the increasing use of heuristic and hybrid techniques for nonlinear and non-convex problems [4].

The integration of renewable generation, however, has made the conventional ED problem considerably more challenging. Wind and solar generation are influenced by weather conditions, forecasting errors, and resource availability, resulting in fluctuations that can affect the balance between electricity generation and demand. For example, research reviewed in this study has incorporated wind uncertainty and energy storage using stochastic scenarios and scenario-reduction techniques [2]. Other studies have examined PV variability, renewable curtailment, and environmental objectives, demonstrating that renewable-rich dispatch problems require broader formulations than conventional fuel-cost minimization [5], [6]. The increasing complexity of these systems has also encouraged the development of uncertainty-based, stochastic, artificial-intelligence, and hybrid optimization methods. This development is consistent with broader research showing that renewable-power-system operation increasingly requires optimization and forecasting techniques capable of handling renewable uncertainty and operational constraints.

Meta-heuristic optimization techniques have consequently received considerable attention in economic dispatch research. Algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Grey Wolf Optimization (GWO), Jaya, Bat Algorithm, and other population-based approaches have been applied to nonlinear and non-convex dispatch problems. The reviewed studies indicate that these methods can provide competitive solutions in terms of generation cost, convergence characteristics, emissions, renewable utilization, and power losses [7],[3], [5],[8],[8]. For instance, the One-to-One Optimization Algorithm (OOBO) has been applied to renewable-integrated dispatch involving thermal, wind, and solar generation, while modified GWO has been employed for combined thermal-solar-wind dispatch [8],[9]. These developments demonstrate the growing interest in algorithms capable of exploring complex solution spaces where conventional mathematical methods may encounter difficulties. The broader literature similarly identifies PSO, GWO, GA, Cuckoo Search, and Differential Evolution among commonly applied meta-heuristics in electric-power-system optimization.

Another important development is the movement from single-objective economic dispatch toward multi-objective optimization. In conventional ED, minimizing generation cost is usually the dominant concern. Renewable-rich systems, however, require consideration of additional objectives such as emission reduction, renewable-energy utilization, power-loss minimization, voltage stability, and renewable curtailment. Studies in the reviewed literature have therefore formulated economic-environmental dispatch and other multi-objective problems involving renewable generation

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[10],[11], [6], [12],[13],[14]. For example, the 2024 study using the African Vulture Optimization Algorithm considered both economic and environmental objectives in a diesel-wind-solar microgrid, while another 2024 study incorporated fuel cost, emissions, power-flow constraints, and gas-network limitations [14].

The increasing complexity of renewable-rich power systems has also encouraged the development of hybrid optimization strategies. Hybrid methods combine two or more optimization mechanisms with the intention of improving exploration, exploitation, convergence, or solution quality. Examples in the reviewed literature include PSO-Bat, PSO-Cat Swarm Optimization, enhanced PSO, and combinations of global meta-heuristic search with local mathematical refinement [15],. Such approaches attempt to overcome some limitations associated with individual algorithms and provide more effective solutions for complex dispatch environments. The 2024 literature on distributed-generation dispatch similarly identifies hybrid approaches as useful for problems involving large-scale systems, multiple objectives, and nonlinear or non-convex characteristics.

Despite these developments, important research gaps remain. Several reviewed studies are based primarily on small or standard IEEE test systems, which may not fully represent the complexity of practical renewable-rich networks. Other studies focus on a particular renewable technology or a single optimization algorithm and provide limited comparative evaluation across different methodological categories [16],[17] , [18], [19], [20]. Furthermore, renewable uncertainty, energy storage, demand response, dynamic loads, network security, transmission congestion, and real-time implementation are not consistently integrated into existing formulations.

The review table also indicates that scalability and real-world validation remain recurring limitations across many studies. Therefore, this review critically examines the development and application of classical and meta-heuristic approaches for economic dispatch in renewable-rich power systems. It compares the characteristics, contributions, and limitations of the major approaches reported in the literature, with particular attention to cost minimization, renewable integration, uncertainty management, environmental objectives, storage, network constraints, convergence, scalability, and practical applicability. The review further identifies areas where existing approaches remain insufficient and highlights the need for more adaptive, robust, computationally efficient, and practically validated optimization frameworks. By bringing these developments together, the study provides a structured basis for understanding how economic dispatch methodologies can evolve to support the reliable, economical, and sustainable operation of increasingly renewable-dominated power systems.

METHODOLOGY OF THE REVIEW

This study employed a systematic literature review approach to provide a comprehensive and objective assessment of existing research on economic dispatch (ED) techniques in modern power systems. The review involved an extensive search of established scientific databases, including IEEE Xplore, ScienceDirect, Springer, Elsevier, and Scopus. Relevant publications were identified using carefully formulated keywords, such as “Economic Dispatch,” “Renewable Energy Integration,” “Metaheuristic Optimization,” “Hybrid ED Models,” and “Stochastic ED.” These search terms were selected to capture a wide range of research on conventional dispatch methods and optimization techniques designed to accommodate renewable energy resources.

Specific inclusion criteria were established to maintain the relevance, credibility, and academic quality of the selected publications. The review considered only peer-reviewed journal articles and conference papers published between 2020 and 2026. Eligible studies were required to examine economic dispatch challenges associated with varying load demands, renewable energy integration, or both. Furthermore, only publications written in English were included to maintain consistency in the evaluation process. These requirements ensured that the reviewed studies reflected significant developments in

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economic dispatch research, particularly in addressing the operational challenges associated with the intermittent nature of renewable energy sources.

Exclusion criteria were equally applied to eliminate publications that did not meet the required standards of technical relevance and practical applicability. Consequently, non-technical articles, grey literature, editorials, review notes, and purely theoretical studies without supporting simulation, modelling, or implementation results were excluded. Duplicate records and publications with incomplete information were also removed to improve the consistency and reliability of the review.

To ensure transparency and facilitate the documentation of the selection process, a procedure inspired by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was adopted. The process commenced with approximately 500 publications identified through the initial database searches. These records were subsequently assessed through successive stages of title screening, abstract evaluation, and full-text examination. Following the application of the established eligibility criteria, approximately 160 publications were retained for detailed analysis. The final collection provided the basis for examining the evolution, performance, limitations, and emerging research opportunities associated with economic dispatch techniques in contemporary power systems. To assist organized evaluation, the selected studies were carefully divided into four primary groups based on their methodological methods and problem-solving techniques:

1. Classical optimization techniques: These include linear programming, nonlinear programming, and dynamic programming, which constitute the fundamental approaches traditionally used to solve economic dispatch (ED) problems.
2. Heuristic and metaheuristic optimization techniques: Methods such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) provide greater adaptability and improved search capabilities when addressing nonlinear and non-convex economic dispatch problems.
3. Hybrid optimization techniques: These approaches combine two or more optimization algorithms to improve solution accuracy, computational efficiency, and robustness when solving economic dispatch problems involving multiple objectives and operational constraints.
4. Stochastic and probabilistic optimization techniques: These methods account for uncertainties in renewable energy generation and electricity demand by incorporating random variables, probability distributions, and uncertainty-based mathematical models into the dispatch optimization process.

This systematic review approach ensures a holistic understanding of the progress, limitations, and potential of current ED methodologies, setting a solid foundation for identifying research gaps and recommending future improvements in optimizing economic dispatch in renewable integrated power systems.

Literature Review

This section discussed the literature review related to ED with renewable rich:

Table 1: The literature review related to ED with renewable rich

Reference	Year	Review topic	Main contribution	Gap relative to the review
[1]	2023	Optimization approaches economic dispatch	Reviews classical, hybrid and for metaheuristic methods such as load PSO, GWO, Jaya and MFO, with showing that advanced hybrid	Gives broad attention to PV-based ELD but provides limited emphasis on real-time implementation, grid security, energy storage, demand

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Reference	Year	Review topic	Main contribution	Gap relative to the review
		renewable energy, particularly PV integration	methods can improve cost and emission performance in renewable-integrated systems.	response and practical large-scale validation.
[21]	2023	Recent developments in economic dispatch problems and their solution methods	Uses a PRISMA-based review of 175 studies and classifies approaches into conventional, uncertainty-based, AI and hybrid methods, highlighting the growing role of intelligent optimization.	Although comprehensive, it does not provide detailed comparative simulation evidence and gives limited treatment to standardized performance evaluation and real-world implementation.
[7]	2020	Renewable-integrated thermal economic load dispatch using a modified directional Bat Algorithm	Develops a modified Bat Algorithm for renewable-thermal ELD and demonstrates improved cost, convergence and resistance to premature convergence on test systems.	Focuses mainly on one enhanced metaheuristic technique rather than systematically comparing the wider range of classical, hybrid, stochastic and AI-based approaches relevant to renewable-rich systems.
[2]	2020	Economic dispatch considering wind uncertainty and energy storage	Combines Monte Carlo scenario generation with SOM-PSO scenario reduction and applies the resulting scenarios to economic dispatch with energy storage.	Concentrates primarily on wind uncertainty and ESS, with less coverage of PV uncertainty, multi-objective operation, environmental impacts, voltage/security constraints and other renewable-rich system requirements.
[3]	2020	Hybrid PSO-Bat Algorithm for renewable-based economic dispatch	Combines PSO and BA to improve solution quality, convergence and computational efficiency across several renewable and thermal dispatch configurations.	Demonstrates the effectiveness of a particular hybrid algorithm but does not comprehensively examine uncertainty modeling, real-time operation, storage, demand response and diverse renewable-rich network conditions.
[22]	2025	Evolution of economic dispatch methods under increasing renewable penetration	Reviews 160 studies covering classical, heuristic, hybrid and probabilistic approaches and explains their suitability under different system and renewable conditions.	Provides a broad methodological overview but, as a synthesis study, offers limited new experimental evidence and limited validation using large-scale real-world power systems.
[10]	2020	Multi-objective dynamic economic dispatch incorporating renewable obligation policies	Develops a dynamic dispatch framework that simultaneously considers operating cost and renewable-energy contribution while enforcing renewable obligation requirements.	Incorporates policy-driven renewable targets but gives comparatively little attention to energy storage, demand response, electricity markets, uncertainty and real-time adaptive optimization.
[23]	2025	Improved lambda-iteration method for	Enhances the classical λ-iteration technique through	Concentrates on improving a classical deterministic technique,

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Reference	Year	Review topic	Main contribution	Gap relative to the review
		non-convex and renewable-integrated economic dispatch	adaptive step-size adjustment, achieving competitive costs and reduced computational time relative to methods such as GA and PSO.	with less consideration of stochastic renewable uncertainty, dynamic loads, emissions, storage and multi-objective dispatch.
[5]	2021	Application of PSO and Sine-Cosine Algorithm to renewable-integrated economic dispatch	Compares PSO and SCA for economic dispatch with PV generation and reports better convergence and lower costs using PSO, with additional benefits from renewable integration.	Uses a relatively small IEEE 14-bus test system and has limited investigation of high renewable penetration, uncertainty, emissions, storage and real-time/dynamic dispatch.
[24]	2025	Multi-area and dynamic multi-area economic dispatch under renewable integration	Reviews MAED and MADED methods, emphasizing classical, metaheuristic, hybrid and machine-learning approaches for dealing with renewable variability, demand changes and market conditions.	Identifies important gaps but provides limited empirical simulation results and insufficient treatment of integrated DERs, ESS, demand response and comprehensive stochastic modeling.
[25]	2026	Dynamic economic-emission dispatch under renewable integration and fuel shortages	Develops a DEED model incorporating PV, wind and limited fuel availability and compares MPA, WaOA and PSO under fuel-shortage conditions.	Focuses strongly on fuel scarcity and bio-inspired algorithms, while broader issues such as uncertainty, storage coordination, demand response, multi-area operation and real-time implementation receive limited attention.
[26]	2025	Optimal renewable power dispatch with voltage stability, congestion and power-loss considerations	Reviews 61 studies and identifies the movement toward multi-objective, hybrid and AI-based methods that simultaneously consider several network-operational requirements.	Highlights the need for integrated optimization but does not itself provide a new unified optimization framework or extensive simulation validation across different renewable-rich systems.
[11]	2022	Hybrid dynamic economic-environmental dispatch using renewable energy and storage	Combines thermal, wind, PV and storage technologies with an improved Mayfly Algorithm and a renewable-output stabilization strategy to reduce cost and emissions.	Addresses economic, environmental and renewable-output stability simultaneously, but further work is needed on renewable forecasting errors, electricity pricing, broader uncertainty and real-time operation.
[27]	2026	Safe deep reinforcement learning and metaheuristic	Proposes a PPO-RLMPA framework combining reinforcement learning, a safety layer, DQN-based adaptation	Represents a more advanced AI-based approach but is tested mainly on benchmark systems; broader geographical diversity,

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Reference	Year	Review topic	Main contribution	Gap relative to the review
		optimization for renewable-integrated dynamic dispatch	and MPA for feasible renewable and pumped-storage dispatch.	stochastic conditions, real-time deployment and automated parameter tuning remain insufficiently explored.
[28]	2026	Fractional Marine Predators Algorithm for nonlinear, non-convex renewable-integrated ELD	Introduces fractional memory into MPA to improve exploration, exploitation, convergence and robustness, including testing on a large system with wind uncertainty and valve-point effects.	Primarily evaluates a single advanced metaheuristic. Multi-objective optimization, real-time applications and hybrid renewable configurations require further investigation.
[6]	2022	Improved PSO for multi-objective economic dispatch in renewable-rich systems	Enhances PSO with reverse learning, mutation and crossover while simultaneously minimizing generation, emission and renewable-curtailment costs.	Addresses several objectives and network constraints but requires further work on advanced constraint handling, real-time data, scalability and dynamic system conditions.
[12]	2021	Modified multi-objective cross-entropy optimization for environmental economic dispatch	Develops an adaptive cross-entropy algorithm with improved search and population-diversity mechanisms for economic and environmental dispatch involving uncertain renewable generation.	Demonstrates strong algorithmic performance but leaves gaps in multi-area operation, additional renewable uncertainties and real-time adaptive dispatch.
[29]	2025	Sustainable economic load dispatch using the Botox Optimization Algorithm	Applies BOA to renewable-integrated economic dispatch and reports improvements in cost, emissions, renewable utilization and convergence on a three-generator system.	The principal limitation is scalability, since evaluation is based on a relatively small system. Larger networks, additional renewable technologies and real-time adaptive operation require investigation.
[4]	2024	Optimization techniques for economic dispatch from distributed generation	Reviews classical and heuristic approaches, including LP, QP, GA, PSO and hybrid methods, with emphasis on cost reduction, constraints and renewable integration in distributed-generation systems.	Provides a useful DG-focused overview but does not deeply integrate renewable uncertainty, energy storage, demand response, real-time optimization, network security and emerging AI-based approaches.
[8]	2024	Renewable-integrated economic load dispatch using the One-to-One Optimization Algorithm (OOBO)	Introduced OOBO for dispatch involving thermal, wind and solar generation. The algorithm achieved lower fuel costs, faster convergence and greater stability than several competing	The study concentrates on cost minimization using one principal meta-heuristic. It gives limited attention to environmental objectives, broader renewable technologies, uncertainty modelling

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Reference	Year	Review topic	Main contribution	Gap relative to the review
			meta-heuristics under different load levels.	and validation on very large or real-world systems.
[30]	2023	Generalized Normal Distribution Optimization (GNDO) for economic dispatch	Applied GNDO to conventional and renewable-integrated ED problems and showed competitive cost, loss and convergence performance compared with GA, WOA, BES and FPA.	Larger and more complex networks, emission objectives, network constraints and real-time dynamic dispatch were not sufficiently addressed.
[31]	2026	Deep-learning-based load forecasting combined with economic dispatch	Combined GRU and LSTM forecasting with GA-based multi-objective dispatch to simultaneously consider operating costs, emissions and wind-generation costs.	The approach was demonstrated on a small IEEE 9-bus system. Renewable uncertainty, larger systems and more advanced optimization strategies require further investigation.
[16]	2026	Enhanced Social Group Optimization for economic dispatch with wind power	Improved SGO using stochastic operators and dynamic updating mechanisms. Tests across systems of up to 220 units showed improvements in cost, stability and computational efficiency.	Further development is needed for parallel implementation, automatic parameter tuning, nonlinear wind modelling and multi-objective/dynamic dispatch.
[32]	2026	Forecast-based Virtual Power Plant dispatch using LSTM	Integrated LSTM forecasts for solar and wind with dynamic VPP scheduling involving PV, wind and battery storage, resulting in reduced grid imports, curtailment and emissions.	Greater attention is needed to extreme-weather conditions, multi-site VPP operation, alternative forecasting models and systematic economic comparison of forecasting approaches.
[13]	2024	Bi-objective economic-emission dispatch in renewable microgrids using AVOA	Applied the African Vulture Optimization Algorithm to diesel-wind-solar microgrids, including validation with real-world microgrid data. It simultaneously reduced costs and emissions while improving renewable utilization.	The framework could be expanded to include unit commitment, demand response, electric vehicles and additional renewable combinations.
[28]	2026	Comparative assessment of conventional, metaheuristic and AI-based economic dispatch methods	Compared TLBO, PSO and GA and found TLBO to provide competitive cost and stronger statistical consistency in the tested system.	The analysis uses a fixed-load 10-unit system and does not adequately incorporate renewable uncertainty, complex objectives or advanced AI methods in real-world renewable-rich networks.

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Reference	Year	Review topic	Main contribution	Gap relative to the review
[29]	2023	Economic load dispatch with photovoltaic integration	Reviews traditional, hybrid and meta-heuristic methods for dealing with nonlinear ELD and PV variability, emphasizing the advantages of advanced methods in renewable integration.	The review is mainly concerned with PV integration and does not comprehensively cover storage, demand response, other renewable sources, real-time dispatch and broader system-security requirements.
[30]	2023	GNDO for conventional and renewable-integrated economic dispatch	Demonstrated that GNDO can achieve low fuel costs and power losses with relatively rapid convergence and limited parameter tuning.	Transmission congestion and other network constraints were not incorporated, while real-time operation and more comprehensive multi-objective formulations remain areas for further research.
[17]	2020	Two-stage energy management of industrial microgrids under renewable uncertainty	Optimized BESS sizing and subsequent microgrid operation using stochastic scenarios for renewable generation, load and market-price uncertainties. Validation used real industrial microgrid data.	Although uncertainty and storage are addressed effectively, integration into a comprehensive real-time controller managing multiple distributed energy resources remains incomplete.
[33]	2025	Multi-energy economic dispatch involving electricity, heat, gas and cooling	Developed a mixed-integer optimization model incorporating flexible loads, CSP and thermal storage while accounting for load and renewable uncertainties.	The study identifies the value of flexible loads and storage but calls for advanced stochastic/ML methods, improved scalability and real-time control.
[18]	2022	Jaya algorithm for renewable-integrated economic load dispatch	Applied the parameter-free Jaya algorithm to nonlinear dispatch involving wind, solar, thermal generation, valve-point effects and emission constraints.	Additional operational constraints such as multi-fuel generation, ramp-rate limits and prohibited operating zones, together with storage and real-time dispatch, remain insufficiently explored.
[34]	2026	Adaptive Artificial Bee Colony for environmental-economic load dispatch	Modified ABC through an adaptive step-size mechanism to simultaneously minimize generation cost, emissions and losses in systems with PV integration.	The work is mainly focused on solar PV; wind integration, hybrid optimization, larger systems and real-world implementation remain open areas.
[14]	2024	Economic-environmental dispatch integrating renewable energy and natural gas	Formulated a multi-objective dispatch problem considering fuel cost, emissions, power-flow constraints and gas-network limitations, using FOFMO, COA and NSGA-II.	Further development is needed to incorporate reinforcement learning, dynamic loads and renewable-generation uncertainty.

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Reference	Year	Review topic	Main contribution	Gap relative to the review
[20]	2024	Multi-strategy PSO for dynamic renewable dispatch in distribution networks	Enhanced PSO with multiple convergence and exploration mechanisms and incorporated network losses, voltage deviation and operating limits.	The study is based on an IEEE 33-bus radial system; scalability, real-time implementation and adaptive parameter control remain important gaps.
[9]	2024	Modified Grey Wolf Optimization for hybrid thermal-solar-wind economic dispatch	Improved GWO using memory, evolutionary operators and stochastic local search, achieving lower operating costs and faster convergence in 13- and 26-unit systems.	The model requires stronger treatment of renewable stochasticity and adaptive parameter tuning, particularly for diverse operating conditions and larger systems.

Economic Dispatch Problem Formulation

The Economic Dispatch (ED) problem is a crucial optimization task in power systems. Its main goal is to determine how to distribute power generation among available units to meet electricity demand at the lowest possible cost, all while respecting various technical and operational limitations. Traditionally, the ED problem operates under the assumption that both electricity demand and the availability of generators are known beforehand. The objective is typically to minimize the overall fuel costs for all active generating units, which is often mathematically represented as a quadratic function of each generator's power output [6].

$$\min F(p) = \sum_{i=1}^{n}(a_i + b_i p_i + c_i p^2) \quad (1)$$

Where a_i, b_i, and c_i are the cost coefficients of the ith generator, Pi is the power output of uniti, and N represents the number of generating units [6]. This optimization is subject to a set of constraints that ensure the feasibility and reliability of system operation:

The total power generated must equal the total system demand plus transmission losses:

$$= \sum_{i=1}^{n} p_i = P_D + P_L \quad (2)$$

Where $P_D$the system is demand and P_L denotes transmission losses.

Each generating unit must operate within its technical minimum and maximum generation boundaries:

$$P_i^{min} \le P_i \le P_i^{max} \quad \text{i=1,2....N} \quad (3)$$

Mathematical Modelling of the Associated Errors and Intermittencies

Accurate mathematical depiction of forecast errors and renewable intermittency is necessary for realistic economic-dispatch (ED) research. Below is a compact, formula-rich treatment you can incorporate into your paper. It covers common stochastic representations, time-series/error models, scenario generation for stochastic programming, chance-constraints, and resilient formulations with practical expressions for reserve sizing and cost integration.

Assume errors are independent identically distributed:

$$\boldsymbol{e_t \sim D(\mu_e\ \sigma_e)} \quad (4)$$

Gaussian: $\boldsymbol{e_t \sim D(\mu_e\ \sigma_e)}$ (convenient but may underestimate tails).

Laplace or Student-t for heavy tails.

Capture temporal correlation using AR (p) or ARMA models:

$$\boldsymbol{e_t = \sum_{i=1}^{p} \emptyset_i e_{t-1} + \varepsilon_t} \quad (5)$$

AR(1) special case:

$$\boldsymbol{e_t = \emptyset_i e_{t-1} + \varepsilon_t} \quad (6)$$

This models persistence in forecast errors and is important for ramp/rate limits.

If error variance changes with time or weather conditions, use GARCH-type models:

$$\sim \aleph\ \boldsymbol{\sigma_e}^2 = \boldsymbol{\alpha_0 + \alpha_1 e_{t-1}}^2 + \boldsymbol{\beta_1 \sigma_{t-1}}^2 \quad (7)$$

Robust ED seeks solutions that are feasible for all ξ in an uncertainty set $\mathcal{U}$:

$$min_{x\epsilon x} max_{\xi \epsilon \mu} C_x^{\ T}\ s.t\ A(\xi)x \le \forall \xi \in \mu \quad (8)$$

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If forecast error is approximated with zero mean and variance $\boldsymbol{\sigma_t}^2$, a simple deterministic reserve level to achieve reliability 1−α is.

$$R_t^{reserve} = z_{1-\alpha}\sigma_t \quad (9)$$

Include reserve procurement cost where $z_{1-\alpha}$ the normal quantile is (or use empirical quantiles for non-Gaussian errors). Total cost objective can c res$R$ reserve t and expected penalty for loss-of-load or spillage. Key reliability metrics to report: Expected Energy Not Served (EENS), Loss-of-Load Probability (LOLP), and expected operating cost under uncertainty $\mathbb{E}$ [Cost]

Research Challenges

Research in renewable-rich power systems still faces significant gaps, often focusing on individual algorithms and benchmark systems rather than comprehensive validation on large-scale, real-world networks [12]. Critical limitations include insufficient modeling of renewable-generation uncertainty, particularly for wind and solar, and limited integration of essential components like energy storage and demand response [1][4][9]. Furthermore, existing formulations often restrict treatment of network security, transmission constraints, and dynamic operating conditions. Scalability issues, inadequate validation with large-scale systems, and the need for adaptive parameter tuning and robust real-time implementation persist. A unified, uncertainty-aware, multi-objective framework integrating diverse renewable technologies, storage, and demand response for practical large-scale operation is still needed [12].

CONCLUSION

The review highlights a significant evolution in Economic Dispatch (ED) techniques, moving from classical deterministic methods to more advanced meta-heuristic, hybrid, stochastic, and AI-based approaches. While classical methods offer computational efficiency for simpler problems, their effectiveness wanes with nonlinearity, uncertainty, and complex constraints inherent in renewable-rich systems. Meta-heuristic algorithms, such as PSO and GWO, demonstrate greater flexibility and promising performance in reducing costs, emissions, and losses in non-convex problems. Hybrid methods further enhance optimization by combining strengths, and AI-based techniques aid in forecasting and adaptive dispatch. However, significant gaps persist, including insufficient uncertainty modeling, limited integration of energy storage and demand response, inadequate consideration of network security, and scalability issues, particularly for large-scale, real-world systems. The ultimate goal is to develop adaptive, robust, and computationally efficient optimization frameworks addressing economic, environmental, and operational requirements simultaneously.

RECOMMENDATIONS

Based on the findings of this systematic study, some significant recommendations arise to guide future re- search and practical developments in Economic Dispatch (ED) under renewable-integrated and dynamically fluctuating power systems. The review has established that while classical mathematical programming approaches are efficient for small-scale and deterministic systems, they are unsuitable for addressing the nonlinearities, uncertain- ties, and stochastic behaviors characteristic of renewable energy sources and modern grid dynamics. Therefore, researchers and practitioners should focus on developing hybrid, data-driven, and adaptive ED frameworks that can effectively manage system complexity, uncertainty, and environmental sustainability. The following are the recommendations for future works.

1. **Adaptive and Robust Optimization Frameworks:** Develop new optimization frameworks that are adaptive, robust, and computationally efficient. These should simultaneously address diverse objectives including economic costs, environmental impacts, and complex operational requirements, moving beyond single-focus solutions to support reliable and sustainable renewable-rich power systems.
2. **Comprehensive Uncertainty Management:** Future research must

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prioritize more sophisticated and integrated modeling of renewable-generation uncertainty and forecasting errors. This involves developing methods capable of handling the inherent variability of wind and solar power to ensure stable and reliable economic dispatch in increasingly renewable-dominated grids.

3. **Enhanced Integration of Flexible Resources:** Increase the focus on thoroughly integrating energy storage systems and demand response mechanisms into economic dispatch problems. These flexible resources are crucial for balancing supply and demand in renewable-rich systems, and their full potential remains underexplored in comprehensive optimization frameworks.
4. **Network Security and Transmission Constraints:** Research should place greater emphasis on incorporating real-world network security and transmission congestion constraints into economic dispatch formulations. Many current studies lack sufficient consideration of these critical elements, limiting their applicability to large-scale, practical power systems.
5. **Scalability and Real-World Validation:** A persistent gap is the insufficient validation of proposed optimization techniques on large-scale or actual power systems. Future work needs to prioritize testing and demonstrating the scalability and practical applicability of new methods in real-world scenarios to ensure their relevance and effectiveness.

Author Contributions

Aliyu Sabo and Muhammad L. Bala writing the first draft; Rabiu Sa'adu compile and editing the first draft; Emmanuel A. Edache writing review and editing the manuscript; Umar Abubakar supervise and coordinate the research. All authors have read and agreed to the published version of the manuscript.

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