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REVIEW ARTICLE

A Review of Metaheuristic Algorithms for Load Forecasting in Smart Grids

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ABSTRACT

Smart electrical grids (SGs) have emerged to advance the management of power systems by solving issues such as voltage instability, reactive loads, power loss, and the integration of renewable energy resources. This review focuses on the applicability of metaheuristic algorithms to energy distribution systems, improved operation, and mitigation of environmental and cost impacts. Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Grey Wolf Optimization (GWO) are identified as effective approaches for dealing with the nonlinear and dynamic complexity of contemporary power systems. The review also addresses the extension of machine learning methods for enhancing load forecasting and real-time energy control, which are key factors for the transition toward innovative and renewable energy systems. Based on recent literature, this research highlights achievements, limitations, and future directions for advancing Smart Grid algorithms. The results emphasize the importance of metaheuristics in redesigning processes that provide optimal, reliable, and sustainable energy facilities.

Keywords: Metaheuristic Algorithms ▪ Smart Grids ▪ Energy Management Systems ▪ Renewable Energy Integration ▪ Load Forecasting ▪ Optimization Techniques

1. INTRODUCTION

Due to the increasing challenges in traditional energy structures and the growing complexity of energy administration, electrical Smart Grids (SGs) have become an innovative concept in power systems. These advanced grids rely on artificial intelligence, optimization algorithms, and constant monitoring to solve fundamental operational problems. Smart Grids have improved energy systems by addressing voltage instability, load power factor, energy losses, and integration of distributed generation. They enhance dependability and effectiveness while supporting global environmental objectives, including reduced greenhouse-gas emissions and increased use of renewable energy [1].

Smart Grids are distinguished from conventional grids by their ability to support real-time management of energy demand and supply. Real-time data analysis and predictive analytics improve power distribution, reduce drawbacks in energy provision, and help avoid service interruptions. Efficient prediction and load management also enhance the use of renewable supplies such as solar and wind energy. These capabilities are essential for countering the variability of renewable energy sources and providing a steady energy supply [2].

Smart Grids support the future vision of efficient, resilient, sustainable, and cost-effective power structures. Subordinate systems make energy distribution faster and more productive through artificial intelligence, remote monitoring, and opti-

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mization algorithms. Their scalability transforms traditional power systems into intelligent networks capable of efficient supply and significant savings [3].

This review focuses on recent information and innovations in Smart Grid technology, particularly in the last five years. Attention is given to optimization techniques including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO), which have been applied to improve energy efficiency and reduce operating costs. These algorithms address energy management through accurate demand prediction, dynamic allocation, and cost-efficient operation. The use of renewable energy sources and energy storage systems is also analyzed to provide viable solutions for uncertainty caused by sharp fluctuations in production and consumption [4].

1.1 Scope of the Review

This review compiles key insights from recent research, addressing optimization techniques in Smart Grids such as GA, PSO, and GWO; renewable energy source (RES) penetration in existing power networks; load forecasting and real-time energy control; demand-response models for smart homes; and future directions for scalable, adaptive, and sustainable energy systems.

1.2 Metaheuristic Algorithms Relevance

Metaheuristic algorithms are important because Smart Grid optimization problems are frequently nonlinear, stochastic, and constrained. Classical deterministic optimization may become computationally expensive or inflexible in such environments, whereas metaheuristics can search large solution spaces and provide near-optimal solutions for scheduling, dispatch, storage, and load forecasting. These algorithms therefore support intelligent, self-sustaining, and sustainable energy networks [5, 6].

1.3 Key Insights

AI and metaheuristic algorithms are useful in energy management systems (EMSs) for forecasting and near-real-time control models that improve reliability and optimization in renewable systems [7]. Advanced neural networks and hybrid optimization models present strong predictive capabilities for identifying energy consumption and generation trends. To integrate RESs properly, fluctuating renewable sources must be considered through scalable algorithms [8]. Metaheuristic demand-response models can also reduce energy demand, costs, and emissions in residential environments [9].

2. LITERATURE REVIEW

The challenges associated with innovative energy systems have accelerated the use of electrical Smart Grids that offer advanced potential for power management. By using artificial intelligence, optimization algorithms, and monitoring, SGs increase system robustness, dependability, and cost-effectiveness. These systems are developed to solve voltage instability, reactive loads, power outages, and incorporation of renewable energy technologies. Their applications extend from household to industrial domains, making SGs an important research area for efficient energy use.

Recent work shows that energy systems benefit from decarbonisation and digitization, particularly when optimization and control techniques are used to coordinate distributed resources [10]. Metaheuristics and multi-criteria decision-making have also been reviewed as contributors to renewable energy systems and sustainable development pillars [11]. Artificial intelligence approaches further support Smart Grid integration and optimization through forecasting, adaptive control, and automated decision-making [12].

Load forecasting remains a central Smart Grid function. Physics-informed neural networks can support load-margin assessment and optimal phasor measurement unit placement [13], while deep-learning methods can improve short-term residential load forecasting across different time horizons [14]. Mathematical modeling and simulation also remain important for optimization and control in energy management [15].

Several studies examine renewable and microgrid applications. A modified Jelly Fish Search Algorithm has been applied to power-system reliability with wind farms [16]. Metaheuristic energy management has also been used for vehicle-to-grid and grid-to-vehicle interaction [17]. Smart home load scheduling with solar photovoltaic generation and demand response has demonstrated reductions in utility bills, emissions, and peak-to-average demand ratio [18]. Honey Badger Algorithm (HBA)-based strategies have been used for real-time scheduling of grid-tied microgrids under uncertainty [19], while Marine Predator Algorithm (MPA) models have been used for efficient microgrid scheduling [20].

In the research presented by Aljribi and Yusupov, the Grey Wolf Optimizer (GWO) is employed to optimize a microgrid system for economic power dispatch. The results show that GWO can reduce total operation cost and ensure efficient load sharing in islanded and grid-connected modes [21]. Gowtham et al. explore microgrids as reliable and sustainable energy sources, proposing a power-aware LSTM with a Deep Brief Network framework to predict grouped energy load and solar energy output while maintaining load balancing [22]. Di Piazza also emphasizes the role of EMSs in the optimal operation of electrical micro- and nanogrids [23].

3. DISCUSSION

The reviewed studies demonstrate that metaheuristic algorithms have become important tools for Smart Grid optimization. Their flexibility makes them suitable for problems involving renewable intermittency, nonlinear load profiles, distributed resources, and operational constraints.

3.1 Optimization Algorithms and Energy Systems

Optimization algorithms are central to the successful operation of modern energy systems. PSO has been observed to be effective where real-time optimization is required because it is relatively simple and fast, making it suitable for energy systems. Similarly, GA and GWO are important for analyzing distributed systems, increasing capacity, and lowering operating expenses [25, 26].

3.2 Renewable Energy Resources Integration

Solar and wind power are stochastic resources, which means they are not constant in supply. This creates problems for

Table 1. Summary of selected literature on optimization and Smart Grid energy management.

Study	Method / Focus	Application	Main Contribution
Rezk et al. [11]	Metaheuristics and MCDM	Renewable energy systems	Reviews progress, bibliometrics, and sustainability contributions.
Judge et al. [12]	Artificial intelligence	Smart Grid integration	Surveys AI approaches for optimization and grid integration.
Irankhah et al. [14]	Deep learning	Residential load forecasting	Improves short-term forecasting over different time horizons.
Archana et al. [16]	Modified Jelly Fish Search	Wind-farm reliability	Supports reliability analysis in power systems with wind integration.
Srihari et al. [17]	Metaheuristic EMS	V2G and G2V energy management	Optimizes electric-vehicle interaction with Smart Grids.
Hua et al. [18]	PSO, GOA, WDO, HG-WDO	Smart home scheduling	Reduces bills, emissions, and peak-to-average demand ratio.
Hassaballah et al. [19]	Honey Badger Algorithm	Grid-tied microgrid scheduling	Provides real-time economic operation under uncertainty.
Al-Wajih et al. [20]	Marine Predator Algorithm	Community microgrids	Minimizes cost while maximizing renewable resource utilization.

standard grid systems. Using metaheuristic algorithms, Smart Grids can address these issues through energy storage coordination, generation scheduling, and load distribution. Research shows that such policies support demand-side response to volatile renewable energy inputs, reduce greenhouse-gas emissions, and decrease reliance on fossil fuels [27, 28].

3.3 Energy Management Systems

The integration of advanced methodologies has strengthened EMSs in Smart Grids. These systems now contain real-time control and optimization functionality, metric-based predictive tools, and autonomous control mechanisms. Algorithms such as HBA and MPA have been used to improve hybrid microgrid control economically and effectively [29, 30].

3.4 Challenges and Future Directions

Several limitations still prevent the effective use of metaheuristic algorithms in Smart Grids. These include scalability for large energy systems, real-time computational burden, and the incorporation of emerging renewable energy technologies. The design of new or hybrid metaheuristic algorithms could provide higher efficiency and sustainability [31, 32].

The application of metaheuristic algorithms in Smart Grids can be described as transformative because they provide practical solutions to important energy-sector problems. Their ability to operate in nonlinear energy systems makes them valuable for green and sustainable energy development. Future work should address scalability and computational burden in large-scale power systems, including distributed state estimation for plug-in hybrid electric vehicles.

4. CONCLUSION

Metaheuristic algorithms enable Smart Grids in contemporary energy management systems. The algorithms considered in this review serve vital objectives in energy strategy because they address distribution, renewable-power incorporation, and overall energy-system improvement. Smart Grids have strengthened energy-sector solutions for voltage instability, reactive-power management, and operational costs through modern computational techniques. This paper highlights PSO, GA, and GWO as important approaches for redesigning energy structures in support of sustainable-development objectives.

A central finding is the potential and variety of metaheuristic algorithms for handling challenges inherent in energy systems. These methods are suitable for nonlinear and stochastic patterns, making them valuable for fluctuating energy requirements. They support electric-resource matching and real-time load forecasting, thereby making the grid more robust and reliable. When integrated with machine-learning methods such as Long Short-Term Memory (LSTM) networks, metaheuristics become more adaptive and can contribute to efficient energy systems.

The review also shows the importance of incorporating renewable electricity into Smart Grids. Metaheuristic algorithms help mitigate renewable intermittency, manage energy storage, and satisfy supply-demand metrics. These developments can reduce emissions and promote cleaner power alternatives. However, future studies should focus on large-scale grid applications, real-time implementation, and improved algorithms capable of adapting to emerging energy problems. Solving these challenges can allow metaheuristic algorithms to transform energy systems toward optimization, sustainability, and stability.

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