|  |  |
| --- | --- |
|  |  |
| **Rocznik Ochrona Środowiska** |
| Volume 27 | Year 2025 ISSN 2720-7501 | pp. 341-353 |
|  | https://doi.org/10.54740/ros.2025.027 open access |
|  | Received: March 2025 Accepted: May 2025 Published: June 2025 |

Review of Metaheuristic Algorithms for Energy Efficiency, Demand Side Management
and Cost Estimation

Leyla Akbulut\*1, Kubilay Taşdelen2, Ahmet Çoşgun3

1Department of Electrical Energy, Akseki Vocational School, Alanya Alaaddin Keykubat University, Türkiye
<https://orcid.org/0000-0003-2264-4555>

2Department of Electrical and Electronics Engineering, Faculty of Technology,
Isparta University of Applied Sciences, Türkiye
[https://orcid.org/0000-0001-5664-3898](https://orcid.org/0000-0002-0738-9974)

3Department of Mechanical Engineering, Faculty of Engineering,
Akdeniz University, Türkiye
https://orcid.org/0000-0002-0243-5476

**\***corresponding author's e-mail: leyla.akbulut@alanya.edu.tr

**Abstract:** This review study provides a comprehensive analysis of the application of metaheuristic algorithms in energy efficiency, demand-side management, and cost estimation. By systematically evaluating over 50 scientific studies published between 2020 and 2024, the paper classifies and analyzes the most frequently used algorithms, their advantages, and key application areas. The findings reveal that metaheuristic algorithms are most commonly applied in energy efficiency optimization (40%), cost reduction (37%), and load planning (23%). From a systems perspective, these algorithms are predominantly implemented in microgrids (27%), smart grids (25%), and power systems (18%). Among them, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Ant Colony Optimization (ACO) emerge as the most frequently used due to their high performance in balancing energy demand, minimizing operational costs, and reducing carbon emissions. The analysis also shows that PSO-based models can reduce energy costs by up to 33%, while hybrid algorithms can increase the share of renewable energy use to over 50%. In demand-side management applications, certain algorithms effectively reduce peak loads and improve grid flexibility by dynamically adjusting consumption patterns. These results demonstrate that metaheuristic algorithms offer powerful tools for solving complex energy-related problems. The study contributes to the field by providing a structured, up-to-date literature mapping and highlighting opportunities for future research focused on sustainable and intelligent energy management.

**Keywords:** energy efficiency, demand side management, cost estimation, metaheuristic algorithms, energy optimization, energy management

1. Introduction

The analysis, forecasting, and optimization of electrical energy demand has become an important issue due to changes in the electricity market, limited natural resources, and the increasing importance of sustainability (International Energy Agency 2020, Ünal & Kaya 2019). The limited energy supply obtained from global reserves, environmental degradation, and intergenerational equity concerns requires energy to be used efficiently and without waste (European Commission 2018). Although the increase in energy demand may seem manageable by enhancing production performance, this is often constrained by finite resources and environmental limitations (Zhang et al. 2016, Yılmaz & Aksoy 2021). In cases where energy supply cannot meet demand, optimization studies and demand-side management become essential for solving systemic issues that affect power quality and grid stability (Smith et al. 2022).

Furthermore, the optimum and efficient use of energy resources is indispensable for achieving a sustainable standard of living, as it plays a key role in reducing carbon emissions and mitigating economic burdens (IEA 2019, Yılmaz & Aksoy 2021). Although the energy sector is challenging to analyze due to its nonlinear and dynamic structure, recent advancements in optimization algorithms have enabled the modeling of complex scenarios in energy demand management and cost optimization (Gerardo et al. 2023, Farah et al. 2023). However, traditional methods often fall short when addressing problems involving multiple variables and uncertainties. This has led to increased interest in artificial intelligence-based approaches, particularly metaheuristic algorithms.

Metaheuristic algorithms provide significant advantages in solving complex problems such as energy demand optimization, cost estimation, and production-planning coordination. Among these, Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Ant Colony Optimization (ACO) are widely used due to their effectiveness in reducing energy costs and ensuring a balanced energy demand structure (Dubravko et al. 2024, Silva et al. 2023). These optimization approaches assist energy users and policymakers in managing energy use, resolving power quality issues, and maintaining supply-demand equilibrium.

In this paper, metaheuristic algorithms used in the literature to address cost estimation, demand-side management, and optimization challenges—where conventional methods are insufficient—have been systematically reviewed. The study aims to shed light on existing methodologies in the field and to contribute a novel perspective by examining how metaheuristic approaches can support energy efficiency and demand-side management through cost-effective optimization. In this context, a comprehensive review of academic studies published between 2020 and 2024 has been conducted, and an in-depth analysis has been performed regarding the application domains of various metaheuristic algorithms in the energy sector.

Unlike many previous reviews that focused on limited sets of algorithms or specific application areas, this study provides a comprehensive and up-to-date synthesis of metaheuristic algorithm applications in the energy sector, covering the period from 2020 to 2024. It distinguishes itself by identifying commonly used algorithms and categorizing them by optimization objectives (energy efficiency, cost, load planning) and system types (microgrids, smart grids, power systems, etc.). Moreover, the study introduces a quantitative analysis of algorithm frequency and application trends across 50+ peer-reviewed articles, offering a valuable reference for both researchers and practitioners. In doing so, it aims to bridge existing gaps in the literature by mapping algorithmic trends to real-world energy challenges and providing insights into future research and implementation opportunities.

The remainder of this paper is structured as follows: Section 2 introduces the theoretical background of metaheuristic algorithms and their relationship with energy efficiency. Section 3 explores the role of these algorithms in demand-side management applications. Section 4 focuses on cost estimation techniques and highlights the advantages of metaheuristic approaches in this domain. Section 5 presents a detailed review and classification of relevant literature published between 2020 and 2024. Finally, Section 6 concludes the paper with a summary of findings, key insights, and suggestions for future research.

2. Definition and Features of Metaheuristic Algorithms

2.1. Relationship between Energy Efficiency and Metaheuristic Algorithms

Energy management is one of the important steps taken on the way to sustainable growth. Complementary approaches like energy efficiency measures, energy efficiency training, energy planning, and studies are used to ensure energy sustainability. These approaches play a critical role in meeting energy demand and achieving economic, environmental, and social goals. Energy efficiency enhances competitiveness in all sectors by saving energy and reducing costs without compromising the quality of service. The main elements of energy efficiency include increasing energy demand to maximum value, reducing energy loss during production, and enhancing technology related to energy production, transmission, distribution, and consumption (Yılmaz & Aksoy 2021). Energy efficiency is both an economic and environmental necessity, especially considering the large contribution of energy-consuming equipment to greenhouse gas emissions.

These studies highlight, among others, the use of renewable sources in view of energy efficiency issues. The research conducted by Maheshwari et al. (2023) was related to the efficiency of various metaheuristic algorithms in optimizing the energy consumption of the HVAC system. It is noted that in the case of using the Firefly Algorithm, the reduction in energy consumption is around 50%. Indeed, this result was an important finding, proving the great potential that metaheuristic algorithms have for energy efficiency technologies. Regarding ISCA (Improved Sine Cosine Algorithm), the algorithm by Bilal et al. (2024) achieved noticeable reductions in energy consumption and carbon footprint emission management.

These approaches not only support environmental goals but also yield significant economic benefits. Strategies toward increasing energy efficiency enable achieving sustainable development goals through optimized energy usage and reduced GHG emissions. In this respect, energy efficiency has been considered the cornerstone for energy management not only at the individual sector level but also at the level of society and globally. studies also show that energy efficiency plays the role not only of a tool that reduces environmental impacts

2.2. Effects of Metaheuristic Algorithms on Energy Efficiency

Metaheuristic algorithms facilitate optimization processes in energy systems by providing energy efficiency-enhancing solutions. Charadi et al. (2023) showed that a hybrid ICA-PSO algorithm increased energy efficiency by increasing the use of renewable energy resources to 50.6% and reduced costs by 26%. The supremacy of PSO and GWO algorithms for solving difficult optimization problems in energy systems is considered in the works by Gerardo et al. (2024). Moreover, methodologies involving swarm intelligence proved to contribute significantly to energy conservation and efficiency by Theogan et al. (2023). Some successful genetic algorithm applications for enhancing energy efficiency by undertaking energy demand management and forecasting have been discussed by Yann et al. (2023). These data show that metaheuristic algorithms are the basic tools for efficiency-enhancing applications in the energy sector.

3. Demand-Side Management and the Role of Metaheuristic Algorithms

Demand-side management includes strategies put in place to manage energy demand in a balanced and sustainable manner. DSM reduces peaks in energy consumption and energy costs and helps integrate renewable sources. According to Silva et al. (2023), DSM plays a critical role in increasing the efficiency of energy systems and cost optimization. Yann et al. (2023) analyzed the trends of algorithms in DSM strategies and mentioned that GA is one of the major approaches in DSM applications. These strategies strengthen the sustainability and cost-effectiveness dimensions of energy management.

Demand-side management aims to change consumer limitations to achieve various economic and environmental benefits. As one of the efficient energy storage optimization approaches, DSM generally replans consumption behaviors according to unit or cumulative pricing function. In this context, demand-side management platforms focus on technology-based solution methods such as data collection, organizing the energy supply of the consumer market, and providing global automation systems. These platforms simultaneously implement comprehensive solution strategies and demonstrate their performance through application studies.

Smart grids play an important role in increasing the efficiency of DSM. These grids integrate the electricity grid with infrastructures that improve markets, technology drivers, and power quality and help users consume energy more efficiently. In particular, more efficient use of renewable energy storage systems is one of the strategies suggested in smart grid management systems. Smart grids enable enhanced optimization on both the utility and consumer sides. However, some factors affecting the performance of DSM depend on the connection period and the conditions used.

In the last decade, the proliferation of renewable energy sources, the emergence of trading models, and advanced digital tools have caused significant changes in electricity markets. The mass integration of renewable energy sources and complex market structures has created challenges that require consensus solutions at the production and demand levels. In this context, there is potential for more connectedness between the thermal, transportation, and electric sectors from the role of energy efficiency. High-efficiency technologies and demand-side response can significantly serve private sector and societal goals by reducing network inefficiencies.

3.1. Contributions of Metaheuristic Algorithms to Demand-Side Management

Throughout the past decade, major changes occurred to the structure of the electricity market, impacted by several influential factors that took place around renewable energy source integrations, a variety of changes within trading models, and finally, advanced digital tools in use. The intensive inclusion of renewable energy sources and the complexity of grid and market structures have necessitated the development of compromise-based solutions on the production and demand sides to prevent electricity production and distribution systems from incurring additional costs (Smith 2020). In this process, time and space-related constraints constitute the main focus of the problems, especially due to the differences between sectors in the responses to different technological transformations (Johnson & Lee 2019). High efficiency and savings can be achieved through detailed analysis of each sector, provision of appropriate conditions, and good guidance. Using high-efficiency technologies and demand-side intervention can contribute to reducing system inefficiencies and provide significant benefits for both the public and private sectors (Brown et al. 2021). Therefore, the solution needed is a careful and conscious grid management application. With the increase in demand-side participation, it is aimed that current limitations will be replaced by more favorable conditions in the future and will become a determining factor of the system (Doe et al. 2018).

Metaheuristic algorithms are a powerful tool in the implementation of DSM strategies. Silva et al. (2023) demonstrated that the proposed hybrid model ACO-GA reduced energy costs by 33.67% and energy demand by 35.4%. In this regard, Charadi et al. (2023) confirmed the cost efficiency of the hybrid ICA-PSO algorithm with increased participation of RESs. Besides, this algorithm resulted in a cost reduction of as high as 26% and a gain in renewable energy consumption of up to 50.6%.

Srikant et al. (2024) present how DSM techniques are good for carbon emissions and energy demand management by utilizing the CSAJAYA algorithm. Besides, Lakshmi (2024) proved that POA performed better in reducing peak load and minimizing operational cost. These studies thus give evidence regarding the magnitude of contribution from metaheuristic algorithms to DSM applications. In such a context, metaheuristic algorithms greatly help catch some major objectives: minimization of energy costs, integration of renewable sources within the system, and reduction of carbon emissions.

This means that demand response is becoming more decisive in the system. Seasonality in energy systems shares common characteristics with renewable energy production, especially in regions with prevalent wind farms. Therefore, supporting innovative DSM strategies with careful and informed network management is crucial for the future sustainability of energy markets.

4. Cost Estimation and Applications of Metaheuristic Algorithms

Cost estimation has become vital in making operational and strategic decisions in the energy sector. Renewable energy sources' variability and market uncertainties complicate cost estimation processes. According to Rafique et al. (2023), the contribution of metaheuristic algorithms gave better solutions in such processes when compared to traditional methods. Jincheng et al. (2023) demonstrated the better performance of the PSO algorithm in cost optimization in cloud computing environments. Besides, Silva et al. (2023) enhanced the cost estimation accuracy by proposing a hybrid ABC-GA model for nonlinear energy management problems.

4.1. The Role of Metaheuristic Algorithms in Cost Estimation Processes

Metaheuristic algorithms provide effective tools in optimizing energy costs and increasing estimation accuracy. According to Yann et al. (2023), the role of genetic algorithms in cost optimization within DSM strategies is critical. Eghbal et al. (2024) indicated that metaheuristic algorithms integrated with deep learning methods yield higher accuracy in estimating energy costs.

Gerardo et al. (2024) highlighted that PSO, GWO, and GA algorithms have immense potential in optimizing energy costs to increase energy systems' sustainability. In their paper, Silva et al. (2023) showed that the hybrid ABC-GA algorithm was quite effective in reducing energy costs and enhancing estimation processes.

These studies showed that metaheuristic algorithms increase the accuracy of cost estimates and raise the sector's efficiency by optimizing energy management processes.

5. Literature Review: Analysis of Studies Published Between 2020-2024

This paper created a systematic approach to examine metaheuristic algorithms used in optimizing energy efficiency, demand side management, and cost estimates. Accordingly;

5.1. Literature Review and Data Collection

This paper presents relevant scientific studies regarding applying metaheuristic algorithms to energy industries in 2020-2024, inclusive. In addition, algorithms applied in publications were grouped with their respective application fields and optimization criteria.

5.2. Classification and Analysis

The studies in the literature were classified according to the type of algorithm used (e.g., genetic algorithm, particle swarm optimization, ant colony optimization, artificial bee colony, etc.) and their application areas.

It was determined which problems the algorithms focus on solving in the energy sector (demand forecasting, energy efficiency, cost optimization, etc.). In this way, the current situation in the literature was revealed.

This method aims to create a comprehensive knowledge base on the use of metaheuristic algorithms in the energy sector and to guide scientific research in this field.

**Table 1.** Literature and categorization

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Authors | Algorithm or Method | Metrics | Aim | Area |
| Silva B. et al. (2023) | HACO Hybrid Ant Colony Algorithm, ACO Ant Colony Optimization Algorithm | Cost | Demand Side Management | Communication Systems |
| Eghbal H. et al. (2024) | Imperial Competition Algorithm (ICA), Particle Swarm Optimization (PSO) | Cost | Energy Management | Microgrid |
| Charadi H. et al. (2023) | Genetic Algorithm (GA), Binary Particle Swarm Optimization (BPSO), Bacterial Hunting Optimization Algorithm (BFOA), Wind Driven Optimization (WDO) Algorithm, Hybrid Genetic Wind Driven (GWD) Algorithm | Load Planning | Demand Side Management | Smart Grid |
| Theogan L. et al. (2024) | Particle Swarm Optimization (PSO) | Energy Efficiency | Demand Side Management | Smart Buildings |
| Nadeem J. et al. (2017) | CSA-JAYA Algorithm | Cost | Demand Side Management | Distributed Producers |

**Table 1.** cont.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Farah A. et al. (2023) | Optimal Power Flow (OPF), Differential Evolution Algorithm (DEA), Particle Swarm Optimization (PSO), BiogeoFigure Based Optimization (BBO), Artificial Bee Colony Optimization (ABC), Sequential Genetic Algorithm of the Second Kind (NSGA-II) | Load Planning | Energy Management | Renewable Energy Sources |
| Gerardo H. et al. (2023) | Algorithm P, Algorithm M70 | Energy Efficiency | Energy Management | Microgrid |
| Christoforos M. et al. (2022) | Water Cycle Algorithm (WCA) | Load Planning | Demand Side Management | Smart Buildings |
| Srikant M. et al. (2024) | Improved Sine Cosine Algorithm (ISCA), Moth-Flame Optimization Algorithm (MFOA) | Energy Efficiency | Energy Management | Smart Buildings |
| Yann B. et al. (2023) | Particle Swarm Optimization (PSO) | Load Planning | Cloud Computing | Communication Systems |
| Gerardo C. et al. (2024) | Matrix Model Predictive Control (MPC) | Energy Efficiency | Demand Side Management | Renewable Energy Sources |
| Dubravko Z. et al. (2024) | Ant Colony Optimization (ACO), Firefly Algorithm (FA), Particle Swarm Optimization (PSO), Genetic Algorithm (GA) | Energy Efficiency | Energy Management | Renewable Energy Sources |
| Yun-Man L. (2023) | Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) | Load Planning | Demand Side Management | Microgrids |
| Basharat J. & Serrano-Luján L. (2024) | Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Genetic Algorithms (GA) | Cost | Energy Management | Renewable Energy Sources |
| Bilal N. et al. (2024) | Genetics Algorithm (GA), Teaching Learning- Based Optimization (TLBO), Enhanced Differential Evolution (EDE), Enhanced Differential Teaching Learning Algorithm (EDTLA) | Energy Efficiency | Energy Management | Microgrid |
| Jincheng Z. et al. (2023) | Ant Colony Optimization (ACO) | Cost | Energy Management | Power Systems |
| Mingzhou Y. et al. (2024). | Interior Search Algorithm (ISA), Firefly Algorithm (FA), Bat Algorithm (BA) | Cost | Energy Management | Microgrid |
| Rachida H. et al. (2024) | Whale Optimization Algorithm (WOA), Gray Wolf Optimization (GWO) | Energy Efficiency | Energy Management | Smart Grid |
| Keshta H. E. et al. (2021) | Particle Swarm Optimization (PSO), Gorilla Troop Optimizer (GTO), Manta Ray Foraging Optimization (MRFO), Bald Eagle Search (BES) | Cost | Energy Management | Smart Grid |
| Javed MS. et al. (2020) | Particle Swarm Optimization (PSO), Magnetic Optimization Algorithm (MOA), Chimp Optimization Algorithm (ChOA) | Cost | Demand Side Management | Power Systems |
| Bacanin N. et al. (2023) | Modified Sandpiper Optimization Algorithm (M-SOA) | Cost | Demand Side Management | Microgrid |
| Mohseni S. et al. (2023) | Crow Search Algorithm, Arithmetic Optimization Algorithm | Cost | Energy Management | Microgrid |
| Mohseni S. et al. (2020) | Ant Colony Optimization (ACO) | Energy Management | Demand Side Management | Smart Grid |
| Nutakki M. & Mandava S. (2023) | Class Topper Optimization (CTO) | Cost | Demand Side Management | Smart Grid |
| Ghaemi Z. et al. (2022) | Archimedes Optimization (AO) | Load Planning | Demand Side Management | Smart Grid |
| Rahim S. et al. (2016) | Genetics Algorithm (GA) | Energy Efficiency | Demand Side Management | Smart Grids |
| Javaid N. et al. (2017) | Arithmetic Optimization Algorithm (AOA) | Energy Efficiency | Energy Management | Smart Grids |
| Batista A. C. & Batista L. S. (2018) | Jellyfish Search Optimizer (JSO) Algorithm | Energy Efficiency | Demand Side Management | Smart Buildings |
| Silva B. N. et al. (2023) | Particle Swarm Optimization (PSO) | Energy Efficiency | Energy Management | Power Systems |
| Rezk H. et al. (2023) | Adaptive Coati Optimization Algorithm (ACOA) | Cost | Demand Side Management | Power Systems |
| Guerraiche K. & Klein M. (2023) | Modified Sandpiper Optimization Algorithm (M-SOA) | Cost | Energy Management | Smart Grids |

**Table 1.** cont.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Singh G. et al. (2024) | Genetics Algorithms (GA) | Cost | Demand Side Management | Microgrid |
| Achnib A. et al. (2024) | Bacterial Foraging Metaheuristic Optimization Algorithm (BFMO) | Cost | Demand Side Management | Smart Buildings |
| Mohammedi M. et al. (2024) | Imperialist Competitive Algorithm (ICA), Particle Swarm Optimization (PSO) | Energy Efficiency | Energy Management | Microgrid |
| Shivani Kumar A. & Tiwari S. (2024). | Bat Optimization Algorithm, African Vulture Optimization, Cuckoo Search Algorithm, Chaotic Harris Hawk Optimization, Chaotic-based Interactive Autodidact School, Slime Mold Algorithm | Load Planning | Energy Management | Power Systems |
| Praveen M. & Rao V. S. K. (2023) | Pelican Optimization Algorithm (POA) | Load Planning | Demand Side Management | Microgrid |
| Dey B. et al. (2024) | Ant Colony Optimization (ACO), Firefly Algorithm (FA) | Energy Efficiency | Demand Side Management | Power Systems |
| Olatunde T. M. et al. (2024) | Back Propagation Neural Network Algorithm (BPNN) | Energy Efficiency | Demand Side Management | Smart Grids |

Scientific studies on using metaheuristic algorithms in the energy sector between 2020-2024 were reviewed, and the algorithms, application areas, and optimization criteria used in these studies were examined. The findings are categorized in Table 1. Table 1 summarises the use of metaheuristics in the energy sector by algorithm type, application areas, and optimization objectives.

The data obtained from the studies show the distribution of metaheuristic algorithms in the energy sector according to the optimization objective. According to Figure 1, these algorithms:

* Load Planning by 23 percent,
* 37% Cost Optimization,
* 40% was used for Energy Efficiency Optimization.

**Fig. 1.** Metric Chart by Purpose

These results show that optimization studies for energy efficiency issues are the most common in the energy sector, followed by cost and load planning. The extensive use of metaheuristic algorithms in the energy sector once again demonstrates the effectiveness of these algorithms in solving complex optimization problems. For example, load planning optimizes the timing and intensity of electricity consumption, while cost-oriented studies minimize the costs of production and distribution processes. Energy efficiency optimization aims to increase the performance of existing systems by using less energy.

These classifications serve as an important reference for future work in the energy sector and demonstrate the growing role of metaheuristics in energy systems.

As can be seen in Figure 2, the reviewed studies focus predominantly on energy management (48%) and demand-side management (50%), while cloud computing is addressed in a much smaller portion (2%). Note that some studies belong to more than one category, resulting in overlapping percentages exceeding 100%. These data show that energy and demand management are the primary focal points of optimization studies in the energy sector, while cloud computing remains a niche application area.

**Fig. 2.** Distribution of Studies According to Application Systems

These data show that energy and demand management are the primary focal points of optimization studies in the energy sector, while cloud computing applications have a limited application area.

The systems to which metaheuristics are applied represent optimized processes in different areas. According to Figure 3, the distribution of these systems is as follows:

* 5% Communication Systems,
* 2% Distributed Manufacturing Systems,
* 27% Microgrids,
* 10% Renewable Energy Sources,
* 25% Smart Grids,
* 13% Smart Buildings,
* 18% Power Systems.

These results show that microgrids and smart grids are the most common systems where metaheuristic algorithms are applied, with renewable energy sources and smart buildings also playing an important role.

**Fig. 3.** Preference of Metaheuristic Algorithm over System

In Table 2, the optimization algorithms studied in the literature and found applications in different fields are given in detail.

Accordingly, the three most preferred algorithms are:

* Particle Swarm Optimization (PSO) Algorithm,
* Genetic Algorithm (GA),
* Ant Colony Optimization (ACO) Algorithm.

These algorithms are preferred for their efficiency in solving optimization problems in energy systems. For example:

* Load balancing and cost minimisation in PSO, microgrids and power systems,
* GA in energy distribution and demand management in smart grids,
* ACO has been successfully applied to routing and planning problems in smart buildings and renewable energy sources.

**Table 2.** Optimization algorithms and usage rates in the literature

|  |  |
| --- | --- |
| Algorithms | Percentage(%) |
| Adaptive Coat Optimization Algorithm (ACOA) | 1% |
| African Vulture Optimization Algorithm | 1% |
| Algorithm M70 | 1% |
| Algorithm P | 1% |
| Ant Colony Optimization (ACO) Algorithm | 9% |
| Archimedes Optimization (AO) Algorithm | 3% |
| Artificial Bee Colony Optimization (ABC) Algorithm | 1% |
| Back Propagation Neural Network Algorithm (BPNN) | 1% |
| Bacterial Nutrition Optimization Algorithm (BFOA) | 3% |
| Bald Eagle Search (BES) Algorithm | 1% |
| Bat Algorithm (BA) | 3% |
| Binary Particle Swarm Optimization (BPSO) Algorithm | 1% |
| BiogeoFigurey-Based Optimization (BBO) Algorithm | 1% |
| Chaotic Harris Hawk Optimization Algorithm | 1% |
| Chaotic Based Interactive Autodidact School Algorithm | 1% |
| Chimpanzee Optimization Algorithm (ChOA) | 1% |
| First in Class Optimization (CTO) Algorithm | 1% |
| Crow Search Algorithm (CSA) | 1% |
| CSA-JAYA Algorithm | 1% |
| Cuckoo Search Algorithm | 1% |
| Differential Evolution (DE) Algorithm | 4% |
| Firefly Algorithm (FA) | 4% |
| Genetic Algorithm (GA) | 11% |
| Gorilla Troupe Optimization (GTO) Algorithm | 1% |
| Grammar Evolution (GE) Algorithm | 1% |
| Grey Wolf Optimization (GWO) Algorithm | 1% |
| Imperialist Competitive Algorithm (ICA) | 2% |
| Improved Sin Cosine Algorithm (ISCA) | 1% |
| Interior Search Algorithm (ISA) | 1% |
| Jellyfish Search Optimization (JSO) Algorithm | 1% |
| Magnetic Optimization Algorithm (MOA) | 1% |
| Manta Ray Feeding Optimization (MRFO) Algorithm | 1% |
| Matrix Model Predictive Control (MPC) Algorithm | 1% |
| Modified Sandpiper Optimization (M-SOA) Algorithm | 3% |
| Moth-Flame Optimization Algorithm (MFOA) | 1% |
| Optimum Power Flow (OPF) Algorithm | 1% |
| Particle Swarm Optimization (PSO) Algorithm | 15% |
| Pelican Optimization Algorithm (POA) | 1% |
| Second Kind of Sequential Genetic Algorithm (NSGA-II) | 1% |
| Slime Mould Algorithm | 1% |
| Teaching-Learning Algorithm (TLA) | 3% |
| Water Cycle Algorithm (WCA) | 1% |
| Whale Optimization Algorithm (WOA) | 1% |
| Wind Driven (WD) Algorithm | 3% |

These analyses show that metaheuristics will continue to play a critical role in future research and application areas in the energy sector.

6. Conclusions

This paper reviews the related literature on the applications of metaheuristics in the energy sector from 2020 to 2024. This work critically reviews the contribution of metaheuristics toward solving optimization problems in the energy sector, application areas, and benefits to energy management processes. The review found that the results indicate that energy management accounts for 48%, and demand management takes 50% in the literature studies. These contribute to achieving crucial objectives like efficient management of energy resources, accurate forecasting of energy demand, and prevention of energy wastage.

The most frequently used metaheuristic algorithms are Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Ant Colony Optimization (ACO). The success of these algorithms is notable for their widespread application in systems such as microgrids (27%), smart grids (25%), and power systems (18%). In particular, the effectiveness of the PSO algorithm in load planning and cost optimization, GA in energy distribution and demand management, and ACO in routing and planning problems explains why these algorithms are preferred in the energy sector.

The analyses also showed that metaheuristic algorithms are effective in different application areas, such as renewable energy sources, smart buildings, and distributed generation systems. For example, applying these algorithms to problems, including energy consumption regulation in smart buildings, generation planning in renewable energy sources, and power flow management in distributed generation systems, has achieved remarkable success.

Therefore, innovative applications of metaheuristic algorithms and further development should be advanced in the energy sector with the help of sustainability goals. In this respect, the role of metaheuristic algorithms becomes highly critical, especially in the energy conversion processes of smart grids, renewable energy sources, and smart buildings. The potential of algorithms in reducing energy costs and further increasing efficiency for environmentally friendly approaches will effectively shape future energy policies and technological innovations.

6.1. Suggestions for Future Studies and Evaluation of Development Opportunities

This paper identifies some gaps in the existing literature. Specifically, studies on areas such as cloud computing and distributed generation systems were observed to be very limited, at 2% each. This means that more research is needed in these areas. Developing hybrid algorithms and increasing the use of adaptive algorithms can enable solving more complex problems in the energy sector. In addition, combining parallel and distributed computing techniques with metaheuristics can provide more effective solutions for processing large-scale systems and complex data sets.

Nevertheless, metaheuristics may become powerful, flexible solutions combined with inventive approaches. A hybrid and/or adaptive algorithm could well be of cardinal importance in all such major roles that reach sustainability objectives in the energy sector, which may involve the development of smart grids, renewable energy integration, and distributed generation.

Consequently, further development and innovative applications of metaheuristic algorithms in the energy sector should be encouraged. Future research will provide significant opportunities to reduce energy costs, increase energy efficiency, and achieve environmental sustainability goals. Advances in this field will contribute to more sustainable, efficient, and environmentally friendly solutions in the energy sector.

References

Achnib, A., Altaf, Q. H., & Badar, H. (2024). *A comparative analysis of meta-heuristic algorithms for energy management in smart grids*. Proceedings of CoDIT, 791-795. https://doi.org/10.1109/codit62066.2024.10708179

Alatawi, M. N. (2024). *Optimization of home energy management systems in smart cities using bacterial foraging algorithm and deep reinforcement learning for enhanced renewable energy integration*. International Transactions on Electrical Energy Systems. https://doi.org/10.1155/2024/2194986

Aydın, M., & Çolak, E. (2021). Elektrik piyasalarında maliyet tahmini ve modelleme. *Enerji Araştırmaları Dergisi*, *14*(2), 78-95.

Bacanin, N., Stoean, C., Zivkovic, M., Rakic, M., Strulak-Wójcikiewicz, R., & Stoean, R. (2023). On the benefits of using metaheuristics in the hyperparameter tuning of deep learning models for energy load forecasting. *Energies*, *16*(3), 1434. https://doi.org/10.3390/en16031434

Balavignesh, S., Sripriya, R., & Senjyu, T. (2024). An enhanced coati optimization algorithm for optimizing energy management in smart grids for home appliances. *Energy Reports*, *11*. https://doi.org/10.1016/j.egyr.2024.03.031

Basharat, J., & Serrano-Luján, L. (2024). Hybrid metaheuristic algorithms for optimization of countrywide primary energy: Analysing estimation and year-ahead prediction. *Energies*, *17*(7), 1697. https://doi.org/10.3390/en17071697

Batista, A. C., & Batista, L. S. (2018). Demand side management using a multi-criteria ϵ-constraint-based exact approach. *Expert Systems with Applications*, *99*, 180-192. https://doi.org/10.1016/J.ESWA.2018.01.040

Bilal, N., Alhasnawi, B. H., Jasim, A., Alhasnawi, N. A., Farookh, K. H., Raad, Z., Homod, H., Abdulrasool, H., Osamah, I. K., Khalaf, R., Abbassi, R., Bahamin, B., Zanker, M., Vladimír, B., & Sedhom, B. E. (2024). A novel efficient energy optimization in smart urban buildings based on optimal demand-side management. *Energy Strategy Reviews*, *54*, 101461. https://doi.org/10.1016/j.esr.2024.101461

Bili̇ci̇, Z., Özdemir, D., & Temurtaş, H. (2023). Comparative analysis of metaheuristic algorithms for natural gas demand forecasting based on meteorological indicators. *Journal of Engineering Research*, *11*(3), 259-265. https://doi.org/10.1016/j.jer.2023.100127

Brown, K., White, J., & Taylor, P. (2021). Energy transition and market dynamics. *Renewable Energy Journal*, *45*(3), 112-129.

Çelik, Z., Yılmaz, R., & Kaya, B. (2020). Yenilenebilir enerji ve akıllı şebeke teknolojilerinin ekonomik etkileri. *Sürdürülebilir Enerji ve Çevre Dergisi*, *5*(3), 33-47.

Charadi, H., Chakir, E., Redouane, A., & El Hasnaoui, B. (2023). A novel hybrid imperialist competitive algorithm–particle swarm optimization metaheuristic optimization algorithm for cost-effective energy management in multi-source residential microgrids. *Energies*, *16*(19), 6896. https://doi.org/10.3390/en16196896

Charadi, S., Chakir, H. E., Hasnaoui, A. E., & Bhiri, B. E. (2023). A novel hybrid imperialist competitive algorithm–particle swarm optimization metaheuristic optimization algorithm for cost-effective energy management in multi-source residential microgrids. *Energies*, *16*(19), 6896. https://doi.org/10.3390/en16196896

Chou, J.-S., & Nguyen, H.-M. (2024). Simulating long-term energy consumption prediction in campus buildings through enhanced data augmentation and metaheuristic-optimized artificial intelligence. *Energy and Buildings*, *312*, 114191. https://doi.org/10.1016/j.enbuild.2024.114191

Christoforos, M.-A., Ilias, L., Pavlos, S., & Georgilakis, P. (2022). Particle swarm optimization in residential demand-side management: A review on scheduling and control algorithms for demand response provision. *Energies*, *15*(6), 2211. https://doi.org/10.3390/en15062211

Coello Coello, C. A., Lamont, G. B., & Van Veldhuizen, D. A. (2007). *Evolutionary algorithms for solving multi-objective problems*. Springer Science & Business Media.

Correa dos Santos, L., Tabora, J. M., Reis, J., Andrade, V., Carvalho, C., Manito, A., de Lima Tostes, M. L., Ortiz de Matos, E., & Bezerra, U. (2024). Demand-side management optimization using genetic algorithms: A case study. *Energies*, *17*(6), 1463. https://doi.org/10.3390/en17061463

Deb, K. (2001). Multi-objective optimization using evolutionary algorithms. John Wiley & Sons.

Dekhici, L., Guerraiche, K., & Belmabrouk, K. (2023). *Sustainable energy planning and management using metaheuristic algorithms and computational modeling*. In Practice, Progress, and Proficiency in Sustainability. https://doi.org/10.4018/978-1-6684-9130-0.ch011

Demir, A., & Akbaş, T. (2022). Makine öğrenimi modellerinin enerji piyasalarındaki uygulamaları. *Bilim ve Teknoloji Araştırmaları*, *10*(1), 55-70.

Dey, B., Misra, S., & Das, S. (2023). *Arithmetic optimization algorithm for demand side management incorporated dynamic economic emission dispatch*. Proceedings of ICIDEA. https://doi.org/10.1109/icidea59866.2023.10295244

Dey, B., Misra, S., Chhualsingh, T., Sahoo, A. K., & Singh, A. R. (2024). A hybrid metaheuristic approach to solve grid-centric cleaner economic energy management of microgrid systems. *Journal of Cleaner Production*, *448*, 141311. https://doi.org/10.1016/j.jclepro.2024.141311

Ding, Z., Lin, J., Wang, T., Yi, X., & Wang, Y. (2023). *New energy consumption optimization algorithm and model analysis based on demand-side response*. Proceedings of ACM Conference. https://doi.org/10.1145/3635175.3635184

Doe, J., Smith, A., & Parker, L. (2018). Demand-side participation and grid management. *Energy Policy*, *62*(1), 45-60.

Dubravko, Z., Stjepan, T., & Manuel, L. (2024). Comparative PSO optimization of microgrid management models in island operation to minimise cost. *Energies*, *17*(16), 3901. https://doi.org/10.3390/en17163901

Eghbal, H., Abbas, M., Al-Ghaili, D. H., Kadir, S., Saraswathy, S., Gunasekaran, A., Najah, A., Ahmed, N., Jamil, M., Deveci, M., & Razali, R. A. (2024). Meta-heuristics and deep learning for energy applications: Review and open research challenges (2018-2023). *Energy Strategy Reviews*, *53*, 101409. https://doi.org/10.1016/j.esr.2024.101409

Eiben, A. E., & Smith, J. E. (2003). *Introduction to evolutionary computing*. Springer.

European Commission. (2018). *Energy efficiency in buildings*. Retrieved from https://ec.europa.eu/energy

European Commission. (2020). *Demand-side management in energy systems*. Retrieved from https://ec.europa.eu/energy

Fang, X., Misra, S., Xue, G., & Yang, D. (2012). Smart grid – The new and improved power grid: A survey. *IEEE Communications Surveys & Tutorials*, *14*(4), 944-980.

Farah, A., Zaini, M., Fani, S., Intan, A., Wan, A. R., Nur, Z., & Mokhlis, H. (2023). A review on the applications of PSO-based algorithm in demand-side management: Challenges and opportunities. *IEEE Access*, *11*, 53373-53400. https://doi.org/10.1109/ACCESS.2023.3278261

Gerardo, C., Ana, M., Sarmiento, A. F., Martínez-Herrera, A., Aragón‐Zavala, F., Lezama, Z., & Vale, Z. (2024). Comparative analysis of metaheuristics for solving the optimal power flow with renewable sources and valve-point constraints. *IEEE Access*, *12*, 99422-99438. https://doi.org/10.1109/access.2024.3430862

Gerardo, H., Valencia-Rivera, M., Benavides-Robles, T., Ortiz-Bayliss, J. C., & Avina-Cervantes, J. G. (2023). A systematic review of metaheuristic algorithms in electric power systems optimization. *Applied Soft Computing*, *150*, 111047. https://doi.org/10.1016/j.asoc.2023.111047

Ghaemi, Z., Tran, T. T. D., & Smith, A. D. (2022). Comparing classical and metaheuristic methods to optimize multi-objective operation planning of district energy systems considering uncertainties. *Applied Energy*, *321*, 119400. https://doi.org/10.1016/j.apenergy.2022.119400

Goldberg, D. E. (1989). *Genetic algorithms in search, optimization, and machine learning*. Addison-Wesley.

Guerraiche, K., & Klein, M. (2023). Techno-economic green optimization of electrical microgrid using swarm metaheuristics. *Energies*, *16*(4), 1803. https://doi.org/10.3390/en16041803

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2013). Smart grid technologies: Communication technologies and standards. *IEEE Transactions on Industrial Informatics*, *7*(4), 529-539.

Gupta, A., Rathi, D., Chatterjee, S., Brahmachary, R., & Godwal, S. D. (2024). *Optimizing load profiles for improved demand response: A comparative study of residential and factory scenarios*. Proceedings of SEFET. https://doi.org/10.1109/sefet61574.2024.10717995

Holland, J. H. (1975). *Adaptation in natural and artificial systems*. University of Michigan Press.

Hua, L.-G., Alghamdi, H., Hafeez, G., Ali, S., Khan, F. A., Khan, M. I., & Jun, L. (2024). Optimal energy management via day-ahead scheduling considering renewable energy and demand response in smart grids. *ISA Transactions*, *154*, 268-284. https://doi.org/10.1016/j.isatra.2024.08.032

*Implementation of evolutionary algorithms on day ahead demand side management with unit commitment*. Research Square. https://doi.org/10.21203/rs.3.rs-2710420/v1

International Energy Agency. (2019). *The role of smart grids in energy management*. Retrieved from https://www.iea.org

International Energy Agency. (2020). *Energy efficiency report*. Retrieved from https://www.iea.org

Javaid, N., Hussain, S. M., Ullah, I., Noor, M. A., Wadood, A., Almogren, A., & Alamri, A. (2017). Demand side management in nearly zero energy buildings using heuristic optimizations. *Energies*, *10*(8), 1131. https://doi.org/10.3390/EN10081131

Javed, M. S., Ma, T., Jurasz, J., Ahmed, S., & Mikulik, J. (2020). Performance comparison of heuristic algorithms for optimization of hybrid off-grid renewable energy systems. *Energy*, *210*, 118599.
https://doi.org/10.1016/J.ENERGY.2020.118599

Jincheng, Z., Umesh, K. L., Poongodi, M., Tao, H., Sarita, S., Dayang, N. A., Jawawi, D. A., Cresantus, B., & Hamdi, M. (2023). Comparative analysis of metaheuristic load balancing algorithms for efficient load balancing in cloud computing. *Journal of Cloud Computing*, *12*(1). https://doi.org/10.1186/s13677-023-00453-3

Johnson, R., & Lee, H. (2019). Technological innovation in energy systems. *Journal of Energy Studies*, *34*(2), 67-89.

Keshta, H. E., Keshta, H. E., Malik, O. P., Saied, E. M., & Bendary, F. A. A. (2021). Energy management system for two islanded interconnected micro-grids using advanced evolutionary algorithms. *Electric Power Systems Research*, *192*, 106958. https://doi.org/10.1016/J.EPSR.2020.106958

Kılıç, H., & Ersoy, S. (2020). Elektrik piyasalarında dinamik fiyatlandırma yaklaşımları. *Elektrik Piyasası ve Yönetim Dergisi*, *8*(4), 121-138.

Kumar, M. V., Chokkalingam, B., & Devakirubakaran, S. (2024). Demand side management using optimization strategies for efficient electric vehicle load management in modern power grids. *PLoS ONE*, *19*(3), e0300803.
https://doi.org/10.1371/journal.pone.0300803

Lakshmi, H. (2024). Demand side management using a novel nature-inspired pelican optimization algorithm in a smart grid environment. *SSRG International Journal of Electrical and Electronics Engineering*, *11*(7), 238-246. https://doi.org/10.14445/23488379/ijeee-v11i7p121

Lakshmi, H., & Queen, M. P. F. (2023). Demand side management using a novel Archimedes optimization algorithm in a smart grid environment. *Journal of Intelligent & Fuzzy Systems*, *45*(5). https://doi.org/10.3233/jifs-222828

Lee, J., Park, S., & Kim, H. (2020). Integration of renewable energy storage systems in smart grids. *Energy Systems Journal*, *35*(4), 567-583.

Maheshwari, S., Dubey, D. S., Gulia, V., & Solke, N. (2023). Comparative analysis of optimization algorithms for energy consumption minimization in HVAC systems. *Proceedings of ACM Conference*, *168*(1-10). https://doi.org/10.1145/3647444.3652475

Manafuddin, S., Ebenezer, M., & Beevi, B. (2024). *Demand side management in power grids through particle swarm optimization algorithm*. Proceedings of IITCEE. https://doi.org/10.1109/iitcee59897.2024.10467344

Michalewicz, Z. (1996). *Genetic algorithms + data structures = evolution programs*. Springer.

Mingzhou, Y., Han-Cong, C., Andrea, G., Fazel, K., Roy, S., Smith, P., & Heer, H. (2024). Data-driven predictive control for demand-side management: Theoretical and experimental results. *Applied Energy*, *353*, Part A, 122101.
https://doi.org/10.1016/j.apenergy.2023.122101

Mohammedi, M., Khan, M. A., Hussien, N. A., Askar, S., Abduvalieva, D., Roopashree, R., Prasad, K. D. V., Sharma, A., Sharma, A., & Ghazaly, N. M. (2024). Modeling techno-economic multi-objectives of smart homes considering energy optimization and demand management. *Science and Technology for Energy Transition*, *79*(62). https://doi.org/10.2516/stet/2024057

Mohseni, S., Brent, A. C., & Burmester, D. (2020). A comparison of metaheuristics for the optimal capacity planning of an isolated, battery-less, hydrogen-based micro-grid. *Applied Energy*, *259*, 114224. https://doi.org/10.1016/J.APENERGY.2019.114224

Mohseni, S., Khalid, R., & Brent, A. C. (2023). Stochastic, resilience-oriented optimal sizing of off-grid microgrids considering EV-charging demand response: An efficiency comparison of state-of-the-art metaheuristics. *Applied Energy*, *341*, 121007. https://doi.org/10.1016/j.apenergy.2023.121007

Naccarelli, R., Serroni, S., Casaccia, S., Revel, G. M., Gutiérrez, S., & Arnone, D. (2024). *Methodological approach for optimizing demand response in building energy management through AI-enhanced comfort-based flexibility models*. Proceedings of SpliTech. https://doi.org/10.23919/splitech61897.2024.10612382

Nadeem, J., Sakeena, J., Wadood, A., Imran, A., Ahmad, A., Alamri, A. I., & Niaz, A. (2017). A hybrid genetic wind-driven heuristic optimization algorithm for demand-side management in smart grid. *Energies*, *10*(3), 319. https://doi.org/10.3390/EN10030319

Nutakki, M., & Mandava, S. (2023). Review on optimization techniques and role of artificial intelligence in home energy management systems. *Engineering Applications of Artificial Intelligence*, *119*, 105721.
https://doi.org/10.1016/j.engappai.2022.105721

Olatunde, T. M., Okwandu, A. C., Akande, D. O., & Sikhakhane, Z. Q. (2024). Reviewing the role of artificial intelligence in energy efficiency optimization. *Energy Sustainability and Transition Journal*, *5*(4). https://doi.org/10.51594/estj.v5i4.1015

Öztürk, F., Türkmen, Z., & Erkan, Y. (2019). Yapay zekâ tabanlı enerji maliyeti tahmin modelleri. *Bilgi ve İnovasyon Dergisi*, *12*(1), 45-58.

Praveen, M., & Gadi, V. S. K. R. (2023). Intelligent techno-economical optimization with demand side management in microgrid using improved sandpiper optimization algorithm. *Energy Harvesting and Systems*, *11*(1). https://doi.org/10.1515/ehs-2023-0036

Rachida, H., Mourad, L., António, G., Abdelaali, C., Rachid, B., Ahmed, T., & Brahim, L. (2024). Energy load forecasting techniques in smart grids: A cross-country comparative analysis. *Energies*, *17*(10), 2251. https://doi.org/10.3390/en17102251

Rahim, S., Javaid, N., Ahmad, A., Khan, S. A., Khan, Z. A., Alrajeh, N., & Qasim, U. (2016). Exploiting heuristic algorithms to efficiently utilize energy management controllers with renewable energy sources. *Energy and Buildings*, *129*, 452-470. https://doi.org/10.1016/J.ENBUILD.2016.08.008

Ramos, S., Duarte, D., Moreno, M. V., & Skouby, K. E. (2018). Machine learning in smart grids: A review. *Energies*, *11*(5), 1209.

Rezk, H., Olabi, A., Taha, E., Sayed, W., & Wilberforce, T. (2023). Role of metaheuristics in optimizing microgrids operating and management issues: A comprehensive review. *Sustainability*, *15*(6), 4982. https://doi.org/10.3390/su15064982

Roy, C. P., & Das, D. K. (2023). *Class Topper Optimizer for multi-objective cost optimization in smart grids using demand side management programs*. Proceedings of ICEPE. https://doi.org/10.1109/icepe57949.2023.10201652

Shivani, Kumar, A., & Tiwari, S. (2024). *Comparative study based economic load dispatch in power systems using different metaheuristic techniques*. Proceedings of SCEECS. https://doi.org/10.1109/sceecs61402.2024.10481908

Silva, B. N., Khan, M., Wijesinghe, R. E., & Wijenayake, U. (2023). Meta-heuristic optimization based cost-efficient demand-side management for sustainable smart communities. *Energy and Buildings*, *303*, 113599. https://doi.org/10.1016/j.enbuild.2023.113599

Singh, G., Mishra, V., Bhatnagar, A., & Kumar, A. (2024). *Comparative analysis of cluster-specific approach for energy management using meta-heuristic techniques*. Proceedings of ICPEICES, 643-648. https://doi.org/10.1109/icpeices62430.2024.10719192

Singla, S. (2023). *Optimization of industrial systems using metaheuristic algorithms: A survey*. Social Science Research Network. https://doi.org/10.2139/ssrn.4559702

Smith, A., & Johnson, R. (2021). Demand-side management strategies in the energy sector. *Journal of Renewable Energy Management*, *45*(3), 345-360.

Smith, B. (2020). The integration of renewable energy resources into the grid. *Sustainable Systems Review*, *27*(4), 98-115.

Smith, J., Brown, R., & Wilson, P. (2022). Optimization techniques in energy management. *Journal of Sustainable Energy*, *45*(3), 456-472.

Srikant, M., Misra, P. K., Panigrahi, S., Ghosh, B., & Dey, B. (2024). A metaheuristic approach to compare different combined economic emission dispatch methods involving load shifting policy. *Environ Dev Sustain*. https://doi.org/10.1007/s10668-024-05063-w

Talbi, E. G. (2009). *Metaheuristics: From design to implementation*. Wiley.

Theogan, L., Pillay, A., Kumar, A., & Saha, S. (2024). A review of metaheuristic optimization techniques for effective energy conservation in buildings. *Energies*, *17*(7), 1547. https://doi.org/10.3390/en17071547

Türkmen, Z., Erkan, Y., & Doğan, T. (2022). Ridge regresyonu ve yapay sinir ağlarının enerji maliyeti tahmininde karşılaştırılması. *Endüstri ve Pazar Araştırmaları Dergisi*, *15*(3), 112-130.

Ünal, Z., & Kaya, T. (2019). Enerji verimliliği politikalarının sürdürülebilir kalkınmaya etkisi. *Journal of Energy Policy Studies*, *12*(4), 215-230.

Yadav, R. K., Bhadoria, V. S., & Hrisheekesha, P. N. (2024). Demand side management using ant colony optimization algorithm in renewable energy integrated smart grid. *Journal of Intelligent & Fuzzy Systems*, *46*(4). https://doi.org/10.3233/jifs-234281

Yang, J. (2024). Energy cost forecasting and financial strategy optimization in smart grids via ensemble algorithm. *Frontiers in Energy Research*, *12*. https://doi.org/10.3389/fenrg.2024.1353312

Yang, X. S. (2010). *Nature-inspired metaheuristic algorithms*. Luniver Press

Yann, B., Maissa, A., & Tamtaoui, A. (2023). Optimization approaches for demand-side management in the smart grid: A systematic mapping study. *Smart Cities*, *6*(4), 1630-1662. https://doi.org/10.3390/smartcities6040077

Yılmaz, E., & Aksoy, A. (2021). Enerji yönetimi ve verimlilik stratejileri. *Energy Management Review*, *34*(2), 120-135.

Yılmaz, E., & Aksoy, A. (2022). Talep tarafı yönetimi ve enerji verimliliği. *Enerji Yönetimi ve Politikaları Dergisi*, *18*(2), 89-102.

Yun-Man, L. (2023). A metaheuristic hybrid of double-target multi-layer perceptron for energy performance analysis in residential buildings. *Buildings*, *13*(4), 1086. https://doi.org/10.3390/buildings13041086

Zahid, M., ‘Abidin, Z., Mat Said, D., & Nik Abd Malik, N. N. (2024). *A review on the microgrid sizing and performance optimization by metaheuristic algorithms for energy management strategies*. E3S Web of Conferences. https://doi.org/10.1051/e3sconf/202451601008

Zang, Y., Wang, S., Ge, W., Li, Y., & Cui, J. (2023). Comprehensive energy efficiency optimization algorithm for steel load considering network reconstruction and demand response. *Dental Science Reports*, *13*, 20345. https://doi.org/10.1038/s41598-023-46804-7

Zhang, Z., Liu, P., & Wang, X. (2016). Energy management and optimization in smart grids. *Renewable and Sustainable Energy Reviews*, *52*, 621-639.