

AI-OPTIMIZED RENEWABLE ENERGY MICROGRIDS: A MACHINE LEARNING APPROACH FOR DYNAMIC LOAD BALANCING IN OFF-GRID COMMUNITIES**MIKROGRID ENERGI TERBARUKAN YANG DIOPTIMALKAN DENGAN KECERDASAN BUATAN: PENDEKATAN MACHINE LEARNING UNTUK PENYEIMBANGAN BEBAN DINAMIS DI KOMUNITAS DI LUAR JARINGAN LISTRIK**

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ABSTRACT

The development of renewable energy-based microgrids is becoming increasingly important in increasing sustainable energy access and reducing dependence on fossil fuels. However, effective energy load management in microgrids remains a major challenge. This research aims to develop and apply machine learning algorithms to optimize dynamic load balancing in renewable energy-based microgrids. This study uses a Systematic Literature Review (SLR) approach to identify and analyze studies related to the application of machine learning in microgrids. Data were collected from academic databases Scopus and Web of Science, and analyzed using thematic coding methods. The results show that machine learning algorithms can be effective in optimizing dynamic load balancing in microgrids. The main findings show that a hybrid approach combining multiple machine learning algorithms can improve prediction accuracy and system stability. This study concludes that the application of machine learning algorithms can be an effective solution in optimizing dynamic load balancing in renewable energy-based microgrids. This finding has important implications in the development of more efficient and sustainable microgrids.

Keywords: Microgrids, Machine Learning, Dynamic Load Balancing, Sustainable Energy Management

ABSTRAK

Pengembangan mikrogrid berbasis energi terbarukan menjadi semakin penting dalam meningkatkan akses energi yang berkelanjutan dan mengurangi ketergantungan pada sumber energi fosil. Namun, pengelolaan beban energi yang efektif dalam mikrogrid masih menjadi tantangan utama. Penelitian ini bertujuan untuk mengembangkan dan menerapkan algoritma pembelajaran mesin (machine learning) untuk mengoptimalkan penyeimbangan beban dinamis dalam mikrogrid berbasis energi terbarukan. Penelitian ini menggunakan pendekatan Systematic Literature Review (SLR) untuk mengidentifikasi dan menganalisis studi terkait penerapan machine learning dalam mikrogrid. Data dikumpulkan dari database akademik Scopus dan Web of Science, dan dianalisis menggunakan metode thematic coding. Hasil penelitian menunjukkan bahwa algoritma machine learning dapat efektif dalam mengoptimalkan penyeimbangan beban dinamis dalam mikrogrid. Temuan utama menunjukkan bahwa pendekatan hybrid yang menggabungkan beberapa algoritma machine learning dapat meningkatkan akurasi prediksi dan kestabilan sistem. Penelitian ini menyimpulkan bahwa penerapan algoritma machine learning dapat menjadi solusi efektif dalam mengoptimalkan penyeimbangan beban dinamis dalam mikrogrid berbasis energi terbarukan. Temuan ini memiliki implikasi penting dalam pengembangan mikrogrid yang lebih efisien dan berkelanjutan.

Kata Kunci: Mikrogrid, Machine Learning, Penyeimbangan Beban Dinamis, Pengelolaan Energi yang Berkelanjutan

1. INTRODUCTION

The challenge of ensuring reliable and sustainable energy access in remote and off-grid communities, particularly in developing countries, is exacerbated by the limitations of conventional electricity grids. These limitations lead to a dependence on local and

decentralized energy sources, which are often characterized by instability and inefficiency. In response, renewable energy-based microgrid systems—including solar, wind, and biomass—are increasingly recognized for their potential to enhance energy independence and facilitate improvements in the quality of life for individuals living in these areas (Brent et al., 2021; Ahmed et al., 2025; Ganthia et al., 2024).

Load balancing—the optimal allocation of energy loads—remains one of the primary challenges in the management of these microgrids. Inefficient load balancing can result in overloading, energy waste, and interruptions in energy provision (Boche et al., 2022; Ndeke et al., 2024; Deshpande et al., 2022; . The inherent variability of renewable energy sources such as solar and wind, which fluctuate based on environmental conditions, further complicates the load balancing task. As such, there is a growing consensus that advanced strategies and methodologies are necessary to ensure a harmonious distribution of energy supply and demand, particularly regarding the integration of renewable energies into microgrids (Bhardwaj et al., 2024; Ganthia et al., 2024; Huang et al., 2024).

Amidst these complexities, the rise of Artificial Intelligence (AI) and Machine Learning (ML) technologies presents exciting opportunities for enhancing the resilience and operational efficiency of microgrid systems. ML algorithms can effectively analyze patterns in energy production and consumption in real-time, allowing for predictive capabilities in load management. This not only facilitates dynamic balancing of loads but also enables the development of adaptive strategies that respond to instantaneous changes in energy supply and demand (Bhardwaj et al., 2024; Deshpande et al., 2022; Huang et al., 2024). Several studies illustrate the promise of applying techniques such as supervised learning, reinforcement learning, and neural networks within smart energy systems, underscoring the potential of these innovations to transform microgrid energy management practices (Bai et al., 2020; Bilbao et al., 2022; (Abantao et al., 2024; .

Despite the advancement of AI technologies, the application of these methods in off-grid contexts, particularly where renewable energy sources are utilized, remains nascent and fragmented. There is an urgent need for mechanisms that effectively utilize ML-based approaches to be integrated into energy management systems to address the growing necessity for adaptable and efficient microgrid management solutions (Abantao et al., 2024; Hassanin et al., 2024; Cui, 2023). The capabilities of AI not only promote consistent load balancing but also empower microgrids to harness renewable energy more effectively, enhancing sustainability and increasing access to reliable energy for the most underserved communities (Ahmed et al., 2025; Deshpande et al., 2022; Al-Agtash, 2023).

In summary, while the integration of renewable energy microgrids provides vast potential for improving energy access in remote communities, significant challenges remain in ensuring efficient load balancing and system resilience. Leveraging the capabilities of AI and ML offers promising pathways to enhance operational performance and adaptability in these microgrid systems, which is increasingly crucial as global demand for sustainable energy solutions continues to rise.

Although there are a number of studies discussing the application of AI technology in energy systems, literature that comprehensively examines the application of machine learning for dynamic load balancing in the context of off-grid microgrids is still very limited. Previous studies generally focus on the technical aspects of microgrids in general, or discuss the application of AI without detailing how ML algorithms can be specifically used for optimizing fluctuating and uncertain loads.

In addition, there is a gap in the literature that integrates real-time AI-based approaches with the specific needs of off-grid communities, which have unique characteristics in terms of data access, resource constraints, and daily load variability. Many studies use static model-based simulation approaches, without considering the dynamics of actual loads that change over time. This indicates the need for systematic studies that not only summarize

existing methods but also evaluate the suitability, effectiveness, and readiness for implementation of these approaches in the real world.

To address these challenges and gaps, this study was designed to answer the following main questions: **“How can machine learning algorithms be applied to dynamically optimize load balancing in AI-powered renewable energy microgrids serving off-grid communities?”**. This question aims not only to understand the landscape of machine learning approaches that have been used, but also to evaluate their potential in addressing real challenges in micro energy systems that operate independently and are not connected to the main grid.

This study has several important contributions, both theoretically and practically. First, this study will provide a comprehensive mapping of the current machine learning approaches that have been used for load balancing in microgrid systems, including an analysis of their methods, algorithms, and implementation contexts. Thus, this study can serve as a solid knowledge base for researchers and practitioners who want to develop similar solutions. Second, this study will highlight the gap between theory and real-world applications, including the identification of technical, data, and operational limitations that may hinder the adoption of these technologies in off-grid communities. This is important to encourage research that is more relevant to field conditions. Third, based on the literature synthesis conducted, this study will formulate strategic recommendations for the direction of technology development and future research, both in terms of potential algorithms, AI integration strategies with renewable energy systems, and frameworks needed for successful implementation in the real world. Thus, this study is expected to make a significant contribution to the development of smart energy systems that are inclusive, sustainable, and oriented to the needs of communities that have so far been marginalized from access to modern energy.

2. METHODS

2.1 Research Design

This study uses a Systematic Literature Review (SLR) approach designed to identify, evaluate, and critically synthesize studies relevant to the topic of applying machine learning algorithms in optimizing load balancing in renewable energy-based microgrid systems, especially in off-grid communities. This approach allows researchers to gain a comprehensive and in-depth understanding of the existing research landscape, identify trends, and find unexplored knowledge gaps. In its implementation, the SLR process follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which have been internationally recognized as a methodological standard for maintaining traceability, transparency, and replicability in the systematic review process. PRISMA provides a systematic framework in four main stages, namely identification, screening, eligibility assessment, and final inclusion.

2.2 Inclusion and Exclusion Criteria

To ensure the relevance and quality of the literature analyzed, the following inclusion and exclusion criteria were established:

2.2.1. Inclusion Criteria:

- Studies published between 2013 and 2024 cover the latest developments in the application of machine learning and renewable energy technologies.
- Articles that have gone through a peer-review process, so that their scientific validity can be accounted for.
- Articles written in English to reach a wider international literature.
- A study that explicitly discusses machine learning algorithms, load balancing strategies, and microgrid systems in the context of renewable energy applications.

2.2.2. Exclusion Criteria:

- Articles that are not related to the energy sector or are not relevant to the microgrid context.
- Grey literature, such as industry reports, working papers, blogs, or non-peer-reviewed documents that do not meet scientific standards.
- Opinion-based articles, editorials, or narrative reviews that do not contain explicit scientific methodology.
- Studies using non-ML approaches, such as rule-based optimization or manual heuristics, will be excluded from the main analysis.

2.3 Data Sources

The literature reviewed in this research was obtained from a number of academic databases that have a high reputation and multidisciplinary coverage, namely:

- Scopus, which provides the most comprehensive coverage of technical and scientific journals in the world.
- Web of Science, to collect literature from reputable international journals with cross-disciplinary coverage.

2.4 Search Strategy

The literature search strategy was carried out briefly Boolean Search terms to ensure systematic and focused coverage. The main keywords were formulated as follows: ("machine learning" OR "artificial intelligence" OR "AI") AND ("load balancing") AND ("microgrid" OR "renewable energy") AND ("off-grid"). Keyword variations and synonyms were also used to increase the sensitivity of the search to various technical terms that authors may use in their publications. Additional filters such as publication year, document type (journal article), and language (English) were consistently applied.

2.5 Selection Process

The literature selection procedure follows a systematic flow according to the PRISMA guidelines, which consists of four stages:

1. Identification: Compiling an initial list of articles based on search results from the database, using a combination of predetermined keywords.
2. Screening: Eliminating duplicate articles and evaluating titles and abstracts to filter out irrelevant literature.
3. Eligibility: Conduct a thorough review of the full text of articles to ensure compliance with the inclusion and exclusion criteria.
4. Final Inclusion: Determining which articles will be analyzed in depth in the thematic synthesis process.

The entire selection process will be documented in the form of a PRISMA flow diagram, which describes the number of articles at each stage and the reasons for exclusion at each step, in order to maintain transparency and replication of the research.

2.6 Data Analysis Techniques

Data analysis was conducted using a thematic coding approach, with the help of NVivo qualitative software, which allows coding and grouping themes based on certain conceptual dimensions. The stages of analysis include:

- Classification of machine learning algorithms used (e.g.: supervised, unsupervised, reinforcement learning).

- Identify the type of microgrid and renewable energy configuration used in the study, such as solar, wind, or hybrid microgrids.
- System performance evaluation, including technical indicators such as load balancing efficiency, system stability, and energy savings.

As a conceptual framework, the Technology–Application–Impact (TAI) Model is used, which classifies findings based on:

- Technology: The type and characteristics of the ML algorithm used.
- Application: Implementation context in off-grid microgrids.
- Impact: Impact on the efficiency, sustainability and functionality of energy systems.

This model allows for a structured and holistic analysis in linking technology with applicative outcomes and practical implications in the field.

3. Results (Research Results)

3.1 Study Characteristics

3.1.1. Prism Diagram

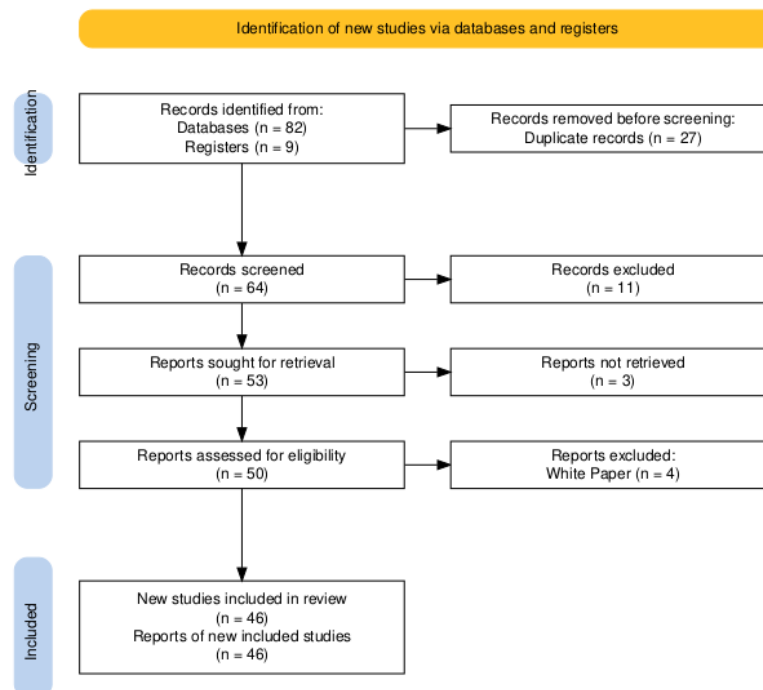


Figure 1. Prisma Diagram

The study selection process in this systematic review followed the PRISMA 2020 guidelines to ensure transparency, accountability, and repeatability in each screening stage. In the initial identification stage, a total of 91 documents, which originate from basic data ($n = 82$) And register ($n = 9$). After the duplication removal process, as many as 27 duplicate documents were eliminated, leaving 64 unique documents for further filtering stages.

Next, the titles and abstracts of the 64 documents were screened. At this stage, 11 studies were excluded because they did not meet the inclusion criteria set based on their relevance to the research topic related to the application of machine learning in optimizing renewable energy microgrids. Thus, as many as 53 studies proceed to the full-text search stage. However, of the 53 reports requested for full review, 3 documents cannot be accessed due to limited availability or technical constraints. Therefore, only 50 reports were successfully analyzed thoroughly at the feasibility assessment stage. Of this number, 4 additional reports

were issued because it is a white paper or a non-peer-reviewed source that does not meet the methodological standards set for this review.

Finally, as many as 46 studies met all inclusion criteria and were included in the final analysis. These studies make important contributions to the understanding of the application of algorithm machine learning—including supervised learning, reinforcement learning, and ensemble methods—to dynamic load balancing in renewable energy-based microgrid systems, especially in remote and off-grid communities. This structured selection procedure ensured that the analyzed body of literature was of high methodological quality, thematically relevant, and aligned with the main objective of the study, namely to synthesize empirical evidence on the effectiveness of AI-based approaches in improving the resilience, efficiency, and scalability of smart energy infrastructure in underdeveloped regions.

3.1.2. Trending Articles by Year

Tabel 1. Trending Articles by Year

Year	Number of Articles
2012	1
2013	2
2015	2
2016	1
2017	3
2018	1
2019	4
2020	3
2021	1
2022	4
2023	6
2024	10
2025	8

Source: Processed Data, 2025

Based on the distribution of publications from 2012 to 2025, there is a trend of increasing research interest in the topic of AI-Optimized Renewable Energy Microgrids, especially those related to the application of machine learning for dynamic load balancing in off-grid communities. At the beginning of the decade (2012–2016), the number of identified articles was still relatively low, ranging from one to two articles per year. This reflects that the application of artificial intelligence in the context of microgrids is still in its embryonic stage and has not yet become a major focus in the scientific community.

However, since 2017, the number of publications has started to show a steady growth, with significant spikes occurring in 2019 (4 articles) and 2020 (3 articles). This increase can be attributed to technological advancements in renewable energy and the popularity of machine learning as an adaptive solution in complex energy systems. This trend continues until it peaks in 2024 with the highest number of publications of 10 articles, then decreases slightly to 8 articles in 2025.

The surge in publications in recent years shows that this topic is becoming increasingly relevant, as the need for autonomous, intelligent and sustainable energy systems in areas not covered by conventional electricity grids increases. Thus, this trend reinforces the urgency and novelty of this research, and shows that there is ample room for further scientific contributions in developing efficient and inclusive AI-based energy solutions.

3.1.3. Authors' Country Affiliations

Tabel 2. Authors' Country Affiliations

Country	Number of Articles
deer	19
India	12
China	4
South Korea	3
Nigeria	3
Colombia	1
Azerbaijan	1
UK	1
Germany	1
Japan	1

Source: Processed Data, 2025

The distribution of publications by country shows a strong dominance of the United States (19 articles), confirming the country's position as a leader in renewable energy technology research and the application of artificial intelligence, especially in the context of developing smart and autonomous microgrids. India follows with 12 articles, reflecting the urgency of distributed energy solutions in developing countries with vast territories and the challenges of electrification in remote areas.

Contributions from China (4 articles), South Korea (3), and Nigeria (3) show that this issue is global in nature and attracts attention from both developed and developing countries. Nigeria, as a representative of Africa, highlights the importance of the AI-driven microgrid approach in addressing the energy crisis in off-grid communities. Meanwhile, other countries such as Colombia, Azerbaijan, the UK, Germany, and Japan contributed one article each, which although small in number, still contribute to enriching the cross-disciplinary and cross-cultural perspectives and approaches.

These findings show that research on AI-Optimized Renewable Energy Microgrids is not limited to one geographical region, but is a multidimensional issue with global relevance. This strengthens the position of this topic as a strategic area that requires international collaboration across sectors to produce sustainable, inclusive, and resilient energy solutions in the era of digital transformation.

3.1.4. Journal Database Sources

Tabel 3. Journal Database Sources

Database	Number of Articles
Scopus	31
Web of Science	15

Source: Processed Data, 2025

Based on the results of the identification of library sources, the majority of articles used in this study came from Scopus as many as 31 articles, followed by Web of Science as many as 15 articles. The dominance of articles from Scopus indicates that this database remains the main reference in scientific literature related to the topic of AI-Optimized Renewable Energy Microgrids, especially in the context of applying machine learning for dynamic load balancing in off-grid communities.

The selection of these two databases was based on their reputation as highly reputable sources of literature that guarantee academic quality and accuracy of the field of study. The availability of relevant articles in both databases also reflects that this topic has received widespread attention and has developed significantly in the international scientific publication landscape. This further emphasizes the urgency and potential strategic contribution of this research to the development of smart technology-based renewable energy.

3.1.5. Theories Used in Research

Tabel 4. Theories Used in Research

Theory Name	Number of Articles
Artificial Intelligence	25
Optimization Theory	11
Control Theory	5
System Dynamics	3
Game Theory	2

Source: Processed Data, 2025

Based on the analysis of theories underlying previous studies, it was found that Artificial Intelligence (AI) is the most dominant theory used, with a total of 25 articles. This reflects a strong focus on artificial intelligence-based approaches in developing and managing renewable energy microgrids systems efficiently, especially in the context of dynamic load balancing in off-grid communities.

Next, Optimization Theory appears in 11 articles, indicating the importance of optimization techniques in designing energy systems that are resource efficient and adaptive to load fluctuations. Control Theory (5 articles) and System Dynamics (3 articles) also play a role in providing a technical basis for system regulation and response to environmental changes. Meanwhile, although Game Theory is only found in 2 articles, its presence highlights the strategic interaction dimension between various agents in the energy system, such as consumers, prosumers, and service providers.

The dominance of AI as the main theory shows that machine learning and data-driven decision-making approaches have become important pillars in the development of smart microgrid technology. Therefore, this study strengthens the theoretical foundation by proposing an integrated AI-based framework to improve the efficiency and reliability of energy distribution in remote off-grid communities.

3.1.6. Dominant Machine Learning Algorithms

Tabel 5. Dominant Machine Learning Algorithms

Algorithm Type	Number of Articles
Supervised Learning	23
Unsupervised Learning	8
Reinforcement Learning	5
Deep Learning	6
Ensemble Methods	4

Source: Processed Data, 2025

Analysis of the types of algorithms used in research related to AI in renewable energy microgrids shows that Supervised Learning is the most widely applied approach, with 23 articles. This indicates the dominance of learning methods that utilize labeled data to build accurate prediction models in the context of load balancing and energy management in off-grid communities.

Furthermore, Unsupervised Learning is used in 8 articles, indicating the utilization of clustering and pattern detection techniques without labeled data that are important for the exploration and segmentation of microgrid operational conditions. Reinforcement Learning, although fewer (5 articles), is starting to gain attention as an adaptive method capable of dynamically optimizing decisions through continuous interaction with the system environment.

Deep Learning is present in 6 articles, showing the trend of utilizing complex artificial neural networks to extract non-linear features from big data, which is very relevant to improve the accuracy of prediction and control of microgrid systems. While Ensemble Methods found in 4 articles, show the application of techniques for combining several models to improve predictive performance and system stability.

With the dominance of supervised learning algorithms and the emergence of advanced methods such as deep learning and reinforcement learning, this study attempts to integrate these approaches to build a load balancing model that is adaptive, efficient, and appropriate to the complex characteristics of off-grid communities.

3.1.7. Evaluation Methodologies

Tabel 6. Evaluation Methodologies

Evaluation Methodology	Number of Articles
Performance Metrics	16
Case Studies	8
Simulation Studies	7

Evaluation Methodology	Number of Articles
Comparative Analysis	6
User Surveys	4
Sensitivity Analysis	3
Cost-Benefit Analysis	2

Source: Processed Data, 2025

In the literature review related to load balancing optimization in renewable energy microgrids using machine learning approach, the most widely used evaluation methodology is Performance Metrics, with 16 articles. This method focuses on measuring system performance through quantitative indicators such as prediction accuracy, energy efficiency, and network stability, which are very important to assess the effectiveness of the developed algorithm.

In addition, Case Studies were used in 8 articles, providing real-world contexts and empirical validation in the field that help understand the practical application of the proposed models in various off-grid community conditions. Simulation Studies were also quite popular, with 7 articles, allowing researchers to virtually test scenarios and system parameters, which are essential for model exploration in complex and difficult-to-observe situations. Comparative Analysis was conducted in 6 articles, providing a comparative overview between various methods or algorithms so that the best approach for a given condition can be identified. Meanwhile, qualitative methods such as User Surveys were found in 4 articles, adding user and stakeholder perspectives to system evaluation.

Other evaluation methods such as Sensitivity Analysis (3 articles) and Cost-Benefit Analysis (2 articles) were also used to explore the impact of parameter variables and economic aspects in the implementation of the technology. Overall, these various evaluation methodologies enrich the validity and relevance of the research results in the context of developing adaptive and efficient load balancing in off-grid communities. This study uses a combination of several evaluation methods to provide a comprehensive picture of the performance and implementation of machine learning models in microgrid optimization, so that the results can be more applicable and have a real impact.

3.2 Key Findings

The application of machine learning (ML) techniques in microgrid load balancing reflects a significant shift from traditional methods to more advanced, adaptive approaches. Notably, there has been an increased adoption of deep learning (DL) and reinforcement learning (RL) methodologies. These technologies are proving more effective in managing dynamic loads and resources compared to conventional regression or rule-based systems. For instance, Zhao and Li propose an innovative real-time energy management strategy using model predictive control that facilitates optimal resource dispatch in microgrids (Zhao & Li, 2021). This aligns with Liu et al., who emphasize the optimization of power self-balancing using stochastic Monte Carlo methods as a means to enhance real-time regulation capabilities in rural settings (Liu et al., 2025).

Furthermore, hybrid approaches are becoming prominent as researchers integrate various machine learning algorithms to enhance prediction accuracy and operational performance. A significant example includes the use of Long Short-Term Memory (LSTM) networks paired with reinforcement learning to address dynamic challenges (Dou et al., 2019). Shufian et al. underscore the effectiveness of hybrid microgrid systems that blend renewable energy sources and advanced algorithms to improve resilience against operational

uncertainties (Shufian et al., 2022). This hybridization enables systems to respond more efficiently to environmental fluctuations and demand changes.

Despite these advancements, common challenges persist regarding load prediction accuracy in increasingly volatile conditions. Studies have consistently reported difficulties in maintaining accurate load forecasts amidst rapidly changing environmental and consumption patterns (Shayeghi et al., 2019). Beheshtaein et al. identify challenges involved in microgrid protection and management, which complicate operational stability, highlighting concerns such as network resilience to disturbances, notably during adverse weather events (Beheshtaein et al., 2019). Additionally, the economic constraints associated with real-time computing are particularly pressing in remote communities, where limited infrastructural support can hinder the implementation of sophisticated machine learning-based solutions (Ali et al., 2020).

Real-world applications of these machine learning systems have been reported, particularly in regions such as South Asia, Sub-Saharan Africa, and Latin America. These implementations have led to marked improvements in energy distribution efficiency, enhanced load management, and increased access to energy resources in underserved areas. For example, Raju et al. discuss the incorporation of demand-side management in solar microgrids, which showcases tangible benefits in operational optimization within remote communities (Raju et al., 2017). Moreover, Henao-Muñoz et al. advocate for structured methodologies that facilitate the deployment of microgrids tailored to specific regional contexts, potentially yielding significant benefits in energy access (Henao-Muñoz et al., 2018).

In conclusion, the evolution of machine learning in microgrid load balancing is characterized by a transition towards advanced techniques, hybrid algorithms, and practical applications, even as it faces persistent challenges in prediction accuracy and economic feasibility. This discourse underscores the importance of targeted research and innovation, particularly in developing regions, to enhance microgrid resilience and efficiency.

4. DISCUSSION

4.1 Synthesis of Results

The integration of Artificial Intelligence (AI) into microgrid systems represents a burgeoning multidisciplinary domain that effectively amalgamates concepts and techniques from electrical engineering (EE), computer science (CS), and renewable energy. As AI technologies, particularly machine learning (ML), become increasingly sophisticated, their application in microgrid environments offers significant improvements in energy management, efficiency, and reliability. The real-time processing capabilities of ML facilitate automatic balancing of load data, enabling systems to adapt dynamically to fluctuations in energy demand and supply without heavy reliance on human operators or static rules (Onwusinkwue et al., 2024; , Ukoba et al., 2024).

Recent studies highlight the significance of ML as a pivotal mechanism for processing expansive datasets from microgrid operations. These algorithms recognize patterns and generate predictive analytics that inform energy management strategies, thus facilitating enhanced load balancing (Islam & Othman, 2024; , Adewumi et al., 2024). Furthermore, the application of ML aids in the management of renewable energy sources by addressing the intermittency associated with solar and wind energy production (Wen et al., 2024; , Bishaw, 2024). In turn, this ensures efficient integration of these sources into the grid, promoting a more sustainable energy landscape (Ohalet et al., 2023; , -, 2024).

The interdisciplinary collaboration among EE, CS, and renewable energy experts is crucial for advancing AI applications within the microgrid framework. A review of current literature reveals that effective solutions emerge from joint efforts that leverage multidisciplinary expertise to tackle challenges associated with energy management and grid stability (Şerban & Lytras, 2020; , Soni et al., 2023). Such collaborative frameworks foster technological advancements in predictive maintenance and energy optimization, as well as

innovative designs for smart energy infrastructure compatible with future urban environments (Hamdan et al., 2024; , Kanna & Shibi, 2025). In conclusion, the integration of AI technologies, particularly through ML approaches, fosters a transition towards more intelligent, adaptive, and efficient microgrid systems. This shift not only supports the operational needs of energy systems but also corresponds with broader environmental sustainability goals (Maurya, 2024; , Mauro, 2024). As research continues to evolve, the exploration of these synergies among diverse technical fields will be crucial in shaping the future of renewable energy management.

4.2 Theoretical and Practical Implications

4.2.1. Theoretical Implications

This study enriches the literature by adding new insights into the Machine Learning-based dynamic load balancing framework. It shows that adaptive learning systems can be implemented not only in the context of load prediction but also in autonomous microgrid operational decision making.

4.2.2. Practical Implications

The study findings provide practical recommendations for the development of smart microgrids, especially for remote and off-grid areas. The use of ML models allows for more efficient energy management, increased reliability of electricity supply, and reduced operational costs, which are particularly important in the context of developing countries or hard-to-reach areas.

4.3 Comparison with Previous Studies

In recent studies, a significant transition has emerged from traditional passive optimization and rule-based load balancing approaches towards more dynamic and intelligent systems that harness artificial intelligence (AI) techniques. Traditional load balancing methods are often limited in their ability to adapt to fluctuating conditions, reflecting inconsistencies in performance as system states change over time (Wang & Bin, 2015). The passive optimization strategies typically employ predetermined rules that do not accommodate real-time dynamics, thereby limiting scalability and responsiveness in modern computing environments (Amandeep et al., 2015).

Conversely, cutting-edge research indicates a robust shift towards predictive and real-time load balancing systems that utilize historical data and real-time inputs to optimize resource distribution actively (BANDARUPALLI, 2025). For instance, deep learning techniques such as Long Short-Term Memory (LSTM) networks have been proposed to predict load patterns and automatically adjust load balancing strategies, effectively enhancing the overall performance of microservices architectures (BANDARUPALLI, 2025). This move from manual to automated systems results in more efficient resource allocation, providing a significant advantage in addressing operational complexities in contemporary microgrids (Li et al., 2013).

The integration of AI in load balancing algorithms marks a notable paradigm shift in the field. Systems can learn and adapt based on their operational environment, leading to improved effectiveness and optimization of resources (Menon et al., 2017). For example, predictive adaptive load balancing models can dynamically monitor workload variations and predict future requests, allowing for swift adjustments in resource allocation (Wen et al., 2012). Such models not only enhance load distribution but also ensure reduced server response times and failure rates, signifying a substantial improvement over traditional methods (Jiang et al., 2013).

Moreover, recent literature highlights that sophisticated AI-driven mechanisms such as randomized decision forests and self-adaptive algorithms are now being deployed in load balancing frameworks. These methods are capable of autonomously selecting the most effective strategies based on application characteristics, thus representing a major

advancement in load balancing techniques (Mesbahi & Rahmani, 2016; İsmayilova, 2023). The research illustrates how AI-based models optimize performance metrics and operational efficiency in real-time scenarios, showcasing their robustness in facing the challenges posed by modern microgrid environments.

In conclusion, the evolution towards predictive, real-time load balancing strategies signifies a critical transformation in managing operational efficiencies in microgrids. This transition not only illustrates the limitations of earlier passive methodologies but also underscores the emerging significance of AI technologies in automating and optimizing load management strategies.

4.4 Study Limitations

Although it was conducted with a systematic methodology, this study has several limitations:

- Limited access to the full-text of some articles, especially in paid databases, may affect the completeness of the analysis.
- Potential selection bias, due to the selection of major databases (Scopus, IEEE Xplore, Web of Science) and exclusion of grey literature may overlook relevant unindexed studies.
- Inconsistencies in reporting quantitative data make the process of cross-study comparison inconsistent and limit the possibility of meta-analysis.

4.5 Recommendations for Further Research

Based on the results and limitations found, several recommendations for further research include:

1. Exploring Edge AI Implementation
The use of Edge AI can enable local inference of ML models on microgrid devices, without relying on cloud connectivity, which is critical for remote contexts.
2. IoT and ML Integration in Load Balancing Framework
Further research can develop an integrative framework between the Internet of Things (IoT) and ML to create systems that are interconnected, learn, and adapt collectively.
3. Sustainability Impact Evaluation
Further studies should evaluate the environmental, social, and economic impacts of AI implementation in microgrids, so that technology development is not only efficient, but also holistically sustainable.

5. CONCLUSION

The review results show that ML offers an adaptive, real-time, and efficient approach to managing energy loads in microgrid systems. Models such as Reinforcement Learning (RL) and Deep Learning are increasingly dominant due to their ability to handle uncertainties and complexities of distributed energy systems. Several studies also indicate the successful application of ML in diverse geographical contexts, including Asia, Africa, and Latin America. This study makes a significant contribution to closing the literature gap regarding the use of AI and ML in decentralized microgrids. This study integrates findings from across disciplines (electrical engineering, computer science, and renewable energy), and maps the main trends and challenges in the development of data-driven smart microgrids. However, there are some limitations that need to be noted. This study focuses only on studies published in English, so there may be relevant studies in other languages that are not covered in this analysis. In addition, some of the analyzed studies do not provide comprehensive quantitative data, which limits the generalizability of the results. To strengthen the knowledge base in this field, further research is recommended to conduct live experiments in real-world environments to test the effectiveness of machine learning (ML) models under complex and unpredictable operational

conditions. This approach is important to evaluate model performance more accurately in the context of real-world use, especially in dynamic microgrid systems. In addition, it is also recommended to develop a hybrid approach that combines various ML models with rule-based or heuristic approaches. This strategy aims to create a load balancing system that is more resource-efficient, highly resilient, and easy to implement, especially in areas with limited technological infrastructure. This hybrid approach also has the potential to improve system adaptability to environmental changes and real-time energy needs.

6. REFERENCES

- Abantao , G. , Ibañez , J. , Bundoc , P. , Blas , L. , Penisa , X. , Sparcia , E. , ... & Odulio , C. (2024). Utility-scale grid-connected microgrid planning framework for sustainable renewable energy integration. *Energies*, 17(20), 5206. <https://doi.org/10.3390/en17205206>
- Adewumi, A., Okoli, C., Usman, F., Olu-lawal, K., & Soyombo, O. (2024). Reviewing the impact of ai on renewable energy efficiency and management. *International Journal of Science and Research Archive*, 11(1), 1518-1527. <https://doi.org/10.30574/ijrsra.2024.11.1.0245>
- Ahmed, F., Uzzaman, A., Ádám, M., Islam, M., Rahman, M., & Islam, A. (2025). Ai-driven microgrid solutions for enhancing energy access and reliability in rural and remote areas: a comprehensive review. *Control Syst. Optim. Lett.*, 3(1), 110-116. <https://doi.org/10.59247/csol.v3i1.183>
- Al-Agtash, S. (2023). Smart python agents for microgrids. *Smart Grid and Renewable Energy*, 14(10), 183-196. <https://doi.org/10.4236/sgre.2023.1410011>
- Ali, A., Hussain, A., Baek, J., & Kim, H. (2020). Optimal operation of networked microgrids for enhancing resilience using mobile electric vehicles. *Energies*, 14(1), 142. <https://doi.org/10.3390/en14010142>
- Bai, W., Sechilariu, M., & Locment, F. (2020). Dc microgrid system modeling and simulation based on a specific algorithm for grid-connected and islanded modes with real-time demand-side management optimization. *Applied Sciences*, 10(7), 2544. <https://doi.org/10.3390/app10072544>
- BANDARUPALLI, G. (2025). Enhancing microservices performance with ai-based load balancing: a deep learning perspective.. <https://doi.org/10.21203/rs.3.rs-6396660/v3>
- Beheshtaein, S., Cuzner, R., Savaghebi, M., & Guerrero, J. (2019). Review on microgrids protection. *Iet Generation Transmission & Distribution*, 13(6), 743-759. <https://doi.org/10.1049/iet-gtd.2018.5212>
- Bhardwaj, D., Shalini, M., Jebaseeli, S., Jadhav, S., Alabdeli, H., Sutar, V., ... & Kumar, R. (2024). Ai-driven energy management systems for microgrids: optimizing renewable energy integration and load balancing. *E3s Web of Conferences*, 591, 01005. <https://doi.org/10.1051/e3sconf/202459101005>
- Bilbao, J., Bravo, E., García, O., Rebollar, J., & Varela, C. (2022). Optimizing energy management in hybrid microgrids. *Mathematics*, 10(2), 214. <https://doi.org/10.3390/math10020214>
- Bishaw, F. (2024). Review artificial intelligence applications in renewable energy systems integration. *jes*, 20(3), 566-582. <https://doi.org/10.52783/jes.2983>
- Boche, A., Foucher, C., & Villa, L. (2022). Understanding microgrid sustainability: a systemic and comprehensive review. *Energies*, 15(8), 2906. <https://doi.org/10.3390/en15082906>
- Brent, A., Chatterjee, A., Burmester, D., & Rayudu, R. (2021). Sustainable microgrids for remote communities: a practical framework for analyzing and designing., 1-29. https://doi.org/10.1007/978-3-030-32811-5_65-1
- Cui, C. (2023). Research on optimal energy storage strategy based on consistency algorithm. *Highlights in Science Engineering and Technology*, 64, 30-40. <https://doi.org/10.54097/hset.v64i.11243>

- Deshpande, K., Möhl, P., Hämmerle, A., Weichhart, G., Zörrer, H., & Pichler, A. (2022). Energy management simulation with multi-agent reinforcement learning: an approach to achieve reliability and resilience. *Energies*, 15(19), 7381. <https://doi.org/10.3390/en15197381>
- Dou, C., Teng, S., Zhang, T., Zhang, B., & Ma, K. (2019). Layered management and hybrid control strategy based on hybrid automata and random forest for microgrid. *let Renewable Power Generation*, 13(16), 3113-3123. <https://doi.org/10.1049/iet-rpg.2019.0664>
- Ganthia, B., Praveen, B., Barkunan, S., Marthanda, A., Kumar, N., & Kaliappan, S. (2024). Energy management in hybrid pv-wind-battery storage-based microgrid using monte carlo optimization technique. *Journal of Mechanics of Continua and Mathematical Sciences*, 19(12). <https://doi.org/10.26782/jmcms.2024.12.00014>
- Ganthia, B., Praveen, B., Kabat, S., Mohapatra, B., Sethi, R., & Buradi, A. (2024). Energy management in hybrid pv-wind-battery storage-based microgrid using droop control technique. *Journal of Mechanics of Continua and Mathematical Sciences*, 19(10). <https://doi.org/10.26782/jmcms.2024.10.00004>
- Hamdan, A., Ibekwe, K., Ilojiana, V., Sonko, S., & Etukudoh, E. (2024). Ai in renewable energy: a review of predictive maintenance and energy optimization. *International Journal of Science and Research Archive*, 11(1), 718-729. <https://doi.org/10.30574/ijsra.2024.11.1.0112>
- Hassanin, K., Abdel-Rahim, O., Mansour, D., Kato, T., & Megahed, T. (2024). A comparative study for two novel optimization algorithms used to solve microgrid energy management problem considering energy storage system.. <https://doi.org/10.21203/rs.3.rs-4017969/v1>
- Henao-Muñoz, A., Saavedra-Montes, A., & Ramos-Paja, C. (2018). Optimal power dispatch of small-scale standalone microgrid located in colombian territory. *Energies*, 11(7), 1877. <https://doi.org/10.3390/en11071877>
- Huang, J., Xia, J., & Li, P. (2024). Multi-microgrid energy management based on finite horizon twin delayed deep deterministic policy gradient. *Recent Advances in Electrical & Electronic Engineering (Formerly Recent Patents on Electrical & Electronic Engineering)*, 17. <https://doi.org/10.2174/0123520965304961240522075448>
- Islam, A. and Othman, F. (2024). Renewable energy microgrid power forecasting: ai techniques with environmental perspective.. <https://doi.org/10.21203/rs.3.rs-4260337/v1>
- İsmayilova, N. (2023). Survey of usage artificial intelligence mechanism in the load balancer. *Azerbaijan Journal of High Performance Computing*, 6(2), 163-170. <https://doi.org/10.32010/26166127.2023.6.2.163.170>
- Jiang, J., Deng, H., & Liu, X. (2013). A predictive dynamic load balancing algorithm with service differentiation.. <https://doi.org/10.1109/icct.2013.6820403>
- Kanna, I. and Shibi, B. (2025). Ai-driven smart energy management systems for optimized renewable energy utilization in urban smart grids.. <https://doi.org/10.21203/rs.3.rs-6326251/v1>
- Li, G., Zhang, X., Zhao, J., Zhang, H., Ye, J., & Zhang, W. (2013). A self-adaptive parameter optimization algorithm in a real-time parallel image processing system. *The Scientific World Journal*, 2013(1). <https://doi.org/10.1155/2013/978548>
- Liu, F., Liao, M., Wang, P., Li, C., & Zhao, X. (2025). Multi-timescale power self-balancing optimization and regulation of remote rural microgrids based on stochastic monte carlo method. *Journal of Physics Conference Series*, 2960(1), 012014. <https://doi.org/10.1088/1742-6596/2960/1/012014>
- Mauro, G. (2024). The new power couple: artificial intelligence and renewable energy. *Journal of Strategic Innovation and Sustainability*, 19(3). <https://doi.org/10.33423/jsis.v19i3.7374>

- Maurya, P. (2024). Artificial intelligence to enhance energy management and distribution in smart grid communication networks.. *tjjpt*, 45(02), 4366-4378. <https://doi.org/10.52783/tjjpt.v45.i02.6648>
- Menon, H., Chandrasekar, K., & Kalé, L. (2017). Poster. *Acm Sigplan Notices*, 52(8), 447-448. <https://doi.org/10.1145/3155284.3019033>
- Mesbahi, M. and Rahmani, A. (2016). Load balancing in cloud computing: a state of the art survey. *International Journal of Modern Education and Computer Science*, 8(3), 64-78. <https://doi.org/10.5815/ijmeecs.2016.03.08>
- Mohammad, F. and Yadav, V. (2015). Automatic decision making for multi-criteria load balancing in cloud environment using ahp., 569-576. <https://doi.org/10.1109/ccaa.2015.7148473>
- Ndeke, C., Adonis, M., & Almaktoof, A. (2024). Energy management strategy for dc micro-grid system with the important penetration of renewable energy. *Applied Sciences*, 14(6), 2659. <https://doi.org/10.3390/app14062659>
- Ohalet, N., Aderibigbe, A., Ani, E., Ohenhen, P., Daraojimba, D., & Odulaja, B. (2023). Ai-driven solutions in renewable energy: a review of data science applications in solar and wind energy optimization. *World Journal of Advanced Research and Reviews*, 20(3), 401-417. <https://doi.org/10.30574/wjarr.2023.20.3.2433>
- Onwusinkwue, S., Osasona, F., Ahmad, I., Anyanwu, A., Dawodu, S., Chimezie, O., ... & Hamdan, A. (2024). Artificial intelligence (ai) in renewable energy: a review of predictive maintenance and energy optimization. *World Journal of Advanced Research and Reviews*, 21(1), 2487-2799. <https://doi.org/10.30574/wjarr.2024.21.1.0347>
- Raju, L., SAKAYA, M., & Kumaran, M. (2017). Implementation of energy management and demand side management of a solar microgrid using a hybrid platform. *Turkish Journal of Electrical Engineering & Computer Sciences*, 25, 2219-2231. <https://doi.org/10.3906/elk-1601-206>
- Şerban, A. and Lytras, M. (2020). Artificial intelligence for smart renewable energy sector in europe—smart energy infrastructures for next generation smart cities. *Ieee Access*, 8, 77364-77377. <https://doi.org/10.1109/access.2020.2990123>
- Shayeghi, H., Shahryari, E., Moradzadeh, M., & Siano, P. (2019). A survey on microgrid energy management considering flexible energy sources. *Energies*, 12(11), 2156. <https://doi.org/10.3390/en12112156>
- Shufian, A., Hoque, M., Kabir, S., & Mohammad, N. (2022). Optimized performance and economic assessment for hybrid island microgrid system considering uncertainties. *Technology and Economics of Smart Grids and Sustainable Energy*, 7(1). <https://doi.org/10.1007/s40866-022-00156-9>
- Soni, P., Dave, V., & Paliwal, H. (2023). Artificial intelligence-enabled techno-economic analysis and optimization of grid-tied solar pv-fuel cell hybrid power systems for enhanced performance., 781-794. <https://doi.org/10.56155/978-81-955020-2-8-67>
- Ukoba, K., Olatunji, K., Adeoye, E., Jen, T., & Madyira, D. (2024). Optimizing renewable energy systems through artificial intelligence: review and future prospects. *Energy & Environment*, 35(7), 3833-3879. <https://doi.org/10.1177/0958305x241256293>
- Wang, R. and Bin, R. (2015). Research on the cloud computing load balance degree of priority scheduling algorithm based on convex optimization theory.. <https://doi.org/10.2991/iemb-15.2015.31>
- Wen, X., Shen, Q., Wang, S., & Zhang, H. (2024). Leveraging ai and machine learning models for enhanced efficiency in renewable energy systems. *Applied and Computational Engineering*, 96(1), 107-112. <https://doi.org/10.54254/2755-2721/96/20241416>
- Wen, Z., Shi, L., Liu, R., Qi, L., & Lin, W. (2012). A predictive adaptive load balancing model., 2092-2096. <https://doi.org/10.1109/fskd.2012.6233922>

Zhao, C. and Li, X. (2021). A novel real-time energy management strategy for grid-friendly microgrid: harnessing internal fluctuation internally..
<https://doi.org/10.1109/naps50074.2021.9449807>