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Review Article

Integration of Renewable Energy with Thermal-Based Power Systems: A Review of Grid Reliability, Optimization, and Storage

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Abstract

Thermal power system are major contributors to power generation and are mostly powered by natural gas, coal, and diesel, all of which are derivatives of petroleum. Aside from their inability to meet energy demands, they have led to growing environmental and economic challenges. Dependence on thermal based power system has further necessitated a transition to sustainable energy systems. This article presents a literature review and statistical analysis based on data obtained from 78 articles published between 2017 and 2025 addressing renewable energy, hybrid power systems, energy storage, optimization strategies, and grid stability. Analysis shows that 50% of the reviewed studies were published in 2024, reflecting a rising research interest. Lithium-ion batteries dominate energy storage (65%), followed by solid-state batteries (10%) and hydrogen fuel cells (6%). Optimization methods are increasingly being adopted, with artificial intelligence-based approaches accounting for 40% and metaheuristic algorithms such as genetic algorithms and particle swarm optimization comprising 30%. However, grid stability continues to be a central challenge as highlighted in 55% of the studies reviewed. Therefore, future work should focus on advanced optimization models to enhance system efficiency and stability. Promising approaches could include techniques that integrate voltage sensitivity analysis with artificial intelligence driven optimization models to improve grid resilience and enable real-time energy management. Furthermore, artificial intelligence driven predictive control, block-chain based energy trading, and IoT enabled smart grids are expected to advance energy networks. By leveraging these innovations, renewable energy sources and thermal power systems can be seamlessly integrated, ensuring a more resilient and sustainable energy future.

Keywords

Renewable Energy Integration, Hybrid Power Systems, Energy Storage, Optimization, Grid Stability, AI-driven Optimization, Voltage Sensitivity Analysis, Smart Grids

1. Introduction

Traditionally, power systems have been controlled by thermal power generation, which is mostly powered by either coal, diesel, and natural gas. Thermal power plants, which is made up of steam and combined-cycle plants, is to an extent known for their scalability, reliability, and ability to meet load demand [1]. However, evidence suggest that the ecological

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concerns linked with fossil fuels is among the most important factor that basically has impacted climate change with greenhouse gas emissions and have stimulated a wide range of technologies toward cleaner energy sources [2]. Power innovations like solar, hydropower, and wind is of interest. They have become some more appropriate choices when compared to traditional thermal system essentially for a wide range of technological developments and cost reductions associated with the wake in skills in areas such as changes in energy capacity, network grid management, and strategy. In order to achieve energy sustainability, improve energy security, and decelerate environmental change, the integration of renewable energy sources (RES) into the electrical grid can play an important role and further addressing the issue related to climate and greenhouse gas emission [3, 4].

Interestingly, the RES was observed to present its difficulties because of their intermittent nature. The intermittent nature is a major problem and of particular concern is the power output which require reciprocal support arrangements and this can frequently be provided by thermal power stations [5]. The intermittent nature of RES which happens to be a challenge have instigated not just the integration of RES with thermal based systems but also the advancement of hybrid systems geared to balance reliability and sustainability [6]. Also, study of the integration of thermal based power systems together with RES shows that it comes with some few economical, technical and policy related difficulties. These include the need for flexible generation capacity, energy storage systems (ESSs), upgrading of existing grids to be compatible with RES configuration, and the need for advanced forecasting tools to predict renewable energy generation [7].

ESSs is an increasingly important area of optimizing power systems. ESSs has been the subject of many classic studies as they enable the storage of electrical energy for later utilization when required. Their significance is particularly pronounced in integrating RES [8]. ESSs unlike alternative energy storage technologies offer some benefits. Firstly, they exhibit high efficiency and possess the capacity to store substantial amounts of energy. Secondly, their versatility allows for deployment across various applications, including backup power systems and energy management solutions. Also, ESSs support grid stability by providing essential services such as frequency regulation and voltage control. Additionally, compared to other storage technologies, they exhibit greater durability and exhibit lower vulnerability to failure. Collectively, these attributes position ESSs as a critical component in the transition toward a more sustainable and resilient energy infrastructure. they demonstrate greater longevity compared to other storage technologies and exhibit lower susceptibility to failure [9].

There is a growing body of literature that recognizes the importance of optimization techniques. Optimization techniques play an important role in addressing the issue of development of efficient and reliable energy management and storage systems, particularly in modern power networks integrating RES. Investigating optimization techniques is a continuing concern as they involve the formulation and implementation of advanced computational approaches pointed at achieving optimal power generation-load balancing in the presence of intermittent RES. In energy system, a fundamental aspect of optimization is the deployment of predictive control algorithms, that leverage on historic and real-time data to forecast renewable energy availability and dynamically control load distribution. These algorithms enable proactive decision-making and ensuring that energy supply meets demand while in the process minimizing operational inefficiencies. Techniques such as model predictive control (MPC), artificial intelligence (AI) based forecasting, and heuristic optimization approaches, including genetic algorithms (GA) and particle swarm optimization (PSO), have been widely employed to enhance system performance. As energy systems continue to evolve with increasing reliance on distributed generation and smart grid technologies, the development of robust and adaptive optimization techniques remains fundamental to achieving sustainable and secure energy infrastructure [10]. The modeling and optimization approaches used for renewable energy integration can be classified into intelligent methods, iterative methods, and computational methods [9].

Recent studies have indicated that RES, mostly wind and solar integration with thermal power stations are on the increase in several countries. For example, solar and wind installations in China, are expected to outpace traditional coal-fired power plants by the year 2028, which will significantly contribute to the renewable energy capacity of the country [11]. Equally, the integration of renewable energy with existing thermal infrastructure in North America and Europe has become a basis of national energy policies intended at decreasing the carbon footprints and enhancing adequate energy availability [12, 13].

This study therefore set out to enable the understanding of the topic for beginners, and the effect of the hybrid model of thermal power systems and RES in having a promising path to a low-carbon, sustainable energy future. The distinction between this review article in comparison to others obtained in the literature is that it states each features of the structures used in each case study.

2. Methodology

This article aims to examine the integration of RES with thermal-based power systems, emphasizing the necessity for optimization, energy storage solutions. The study provides an overview of the composition of these integrated systems, the key components utilized in their development, and the optimization techniques employed to enhance their performance.

To achieve this objective, a comprehensive literature review was conducted, focusing on articles published between 2017 and 2025 across various academic repositories and search engines, including Zenodo, Academia, Google Scholar, and others. A total of 78 articles related to the integration, optimization, and ESSs using diverse methodologies, were analyzed and classified. The article selection process is illustrated in Figure 1.

Figure 1 illustrates the methodology employed for the systematic literature review. The process follows a structured approach consisting of four basic stages: identification, screening, eligibility, and inclusion, each defined by specific selection and search criteria. Initially, the search was conducted based on titles and keywords, including "Renewable Energy Systems," "Integration of RES," "RES Optimization," and "Energy Storage System," yielding a total of 1,902 articles related to renewable energy systems.

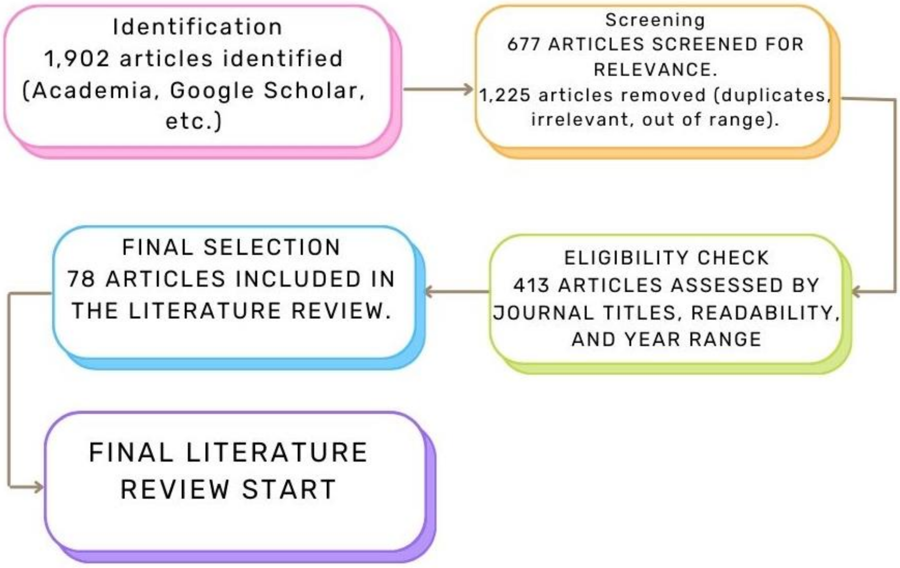

Figure 1. *Article selection process.*

During the screening phase, 1,225 articles were excluded due to duplication, irrelevance, or falling outside the specified time frame. In the eligibility stage, additional selection criteria were applied, focusing on journal type, publication year, and readability, which resulted in the exclusion of 264 articles. Consequently, 413 articles met the eligibility criteria, and after a final evaluation, 78 articles were selected for inclusion in the review.

3. Integration of RES with Thermal-Based Power Systems

The integration of RES with thermal-based power systems is an important component and a vital area of research aimed at enhancing energy security through sustainability, reducing carbon emissions, and improving grid stability. This section of the reviewed literature provides an understanding into various aspects and phases of RES integration which includes energy storage technologies, grid resilience, and optimization strategies. Articles on renewable energy integration, which in total fourteen, span from 2021 to 2025, demonstrating the increasing scholarly attention toward renewable energy integration in power systems. The publication distribution indicates a concentration of work done in the year 2023 and 2024 with 26.67% each, having 2025 contributions accounting for 20%, reflecting on the ongoing advancements in the field. The major source of publications is IEEE (73.33%), followed by Research Gate and other sources (26.67%), reinforcing the technical thoroughness and peer-reviewed nature of the selected studies.

Table 1. *Literature on Renewable Energy Integration.*

Title	Year	Summary	Limitation	Gap	Reference
Advancing Green Energy Integration in Power Systems for Enhanced	2024	This study has identified the challenges of integrating RES into power systems and has proposed	A limitation of this study is that it focuses primarily on energy	A further study could assess real-world case studies to validate the	[14]

Title	Year	Summary	Limitation	Gap	Reference
Sustainability: A Review		a framework leveraging advanced energy storage mechanisms.	storage solutions and did not address all integration challenges.	proposed framework.	
Integration of Renewable Energy Source in Transmission Grids: Issues and Perspectives	2021	This research has also shown and examined the integration of RES into transmission grids, discussing technologies, impacts, and solutions.	Whilst this study is limited to transmission grids, it does not cover distribution networks.	The main weakness of this study was the paucity of insufficient exploration of economic implications of integration.	[15]
Integration of Renewable Energy Sources in Energy Systems: Management, Security and Sustainability	2025	The most obvious finding to emerge from this study is that it addresses management, security, as well as sustainability in integrating RES into energy systems and also analyzing technological solutions.	The most important limitation lies in the fact that the broad focus of the work may dilute depth in specific areas.	Although the current study is based on a broad focus, it limited discussion on policy frameworks supporting integration.	[16]
Recent Advances in Energy Storage Systems for Renewable Source Grid Integration: A Comprehensive Review	2022	The relevant of ESSs is clearly supported by their applications in grid integration, and associated power converters.	This current study is limited by primarily focuses on energy storage, it was not possible to look at other integration aspects.	Future studies needs more analysis on cost-effectiveness and scalability of storage solutions.	[17]
A Critical Review of the Integration of Renewable Energy Sources with Various Technologies	2025	This study have discussed the challenges and differences in integrating wind, solar, and hydro power into existing power systems compared to conventional plants.	This study is limited by the lack of information on detailed solutions to identified challenges.	Considerably more work will need to be done to determine hybrid systems combining multiple RES.	[18]
Hybrid Energy Storage Systems for Renewable Energy Integration: An Overview	2024	One of the more significant finding to emerge from this study is that it explores the use of hybrid ESSs to address the challenges of RES integration due to their intermittent nature.	This study is limited by it concentration on storage solutions. It did not discuss more on other integration strategies.	A further study could assess real-world application data to support theoretical findings.	[19]
Grid-Forming Technologies for Resilient Renewable Energy Integration into Power Systems: A Review	2024	This study reviewed grid-forming technologies as an inventive approaches to guarantee stability in power systems with high RES integration.	This study focused on technical aspects. Less attention was given to economic feasibility.	Future work is expected to explore the integration with existing grid infrastructure.	[20]
Impacts of Renewable Energy Integration on Power System Stability	2023	This study has examined the effects of integrating RES. One of the significant finding is the impact on the power system stability, highlighting both benefits and challenges.	This current study is limited to stability aspects, whilst other operational challenges are not covered.	A further study is expected on more comprehensive risk assessment studies.	[21]
Renewable Energy Integration in Power System: Clarification on Stability Indices	2023	This research has also shown and examined the challenges in maintaining system stability with increasing RES integration. It also clarifies the use of stability indices.	This research focused solely on technical aspect and it's not accessible to non-specialist stakeholders.	Although the current study is based on a broad focus, it needs practical guidelines for implementing stability measures.	[22]
Integration of Renewable Energy Resources and Implications: A Review	2022	This study reviewed the implications of integrating RES into power systems; It also discussed	Whilst this work took a broad scope, it could overlook specific re-	Considerably more work will need to be done to determine regu-	[23]

Title	Year	Summary	Limitation	Gap	Reference
		the challenges and advancements in technology and grid management.	gional challenges.	lations and market-based solutions.	
Hydrogen Production by Renewable Energy and Future Trend in China	2023	This study has examined hydrogen energy as a clean, flexible, zero-carbon secondary energy source, and it discussed its role in stabilizing renewable energy fluctuations as a way of optimizing power system operations.	Whilst this work focuses on China's context, its findings may not be directly applicable globally.	Limited discussion on large-scale implementation challenges.	[24]
Artificial Intelligence in Renewable Energy Integration for Smart Grids	2024	This work evaluate the role of AI in optimizing RES integration, it also focused on predictive maintenance and load balancing.	A limitation of this study is it heavy dependence on high computational power and accessibility issues for developing nations.	A further study would need a real-world applications with large-scale deployments.	[25]
Economic and Technical Feasibility of Large-Scale RES Integration in Developing Countries	2021	This research has also shown and examined the economic and technical barriers to large scale RES integration, with case studies from Africa and Asia.	The most important limitation lies in the fact that it focuses strictly on macroeconomic impacts. The microeconomic aspects are not well addressed.	Future work is requires to make a deeper analysis of grid resilience under different policy scenarios.	[26]
Optimization Strategies for Renewable Energy Integration in Hybrid Power Systems	2023	The most obvious finding to emerge from this study is that it investigates different optimization techniques for hybrid power systems, take a look at AI-based and classical optimization.	The most important limitation lies in the fact that complex optimization models may well possibly not be implementable.	A further study is expected to look at a real-world validation of the proposed optimization techniques.	[27]

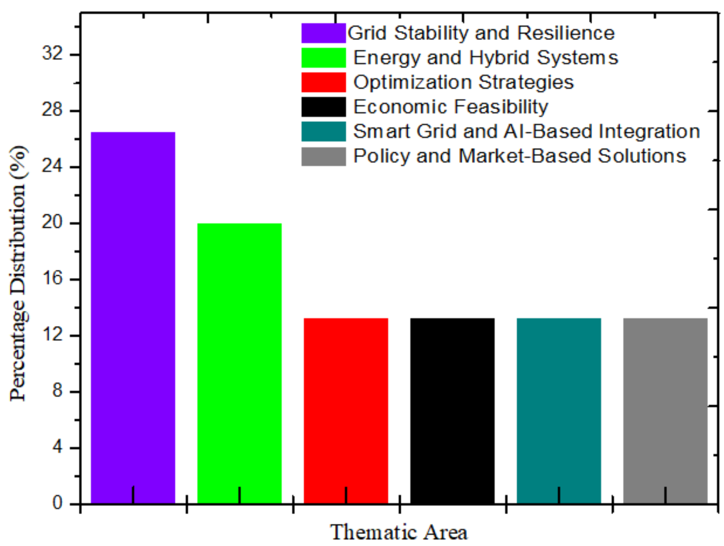

Figure 2. *The key thematic focus across the literature.*

The outcome in Table 1 indicates that the thematic distribution of the reviewed articles suggest that while grid stability remains a major concern, what emerges from the Table 1 also suggest that there is an emergent emphasis on economic, policy, and technological developments that support the large scale acceptance of renewable energy sources as shown in Figure 2.

One interesting finding is that several limitations are persistent in the reviewed studies. The most significant is that 40% of the articles lack real-world validation, largely depending mostly on hypothetical models or simulations without experimental case studies. Furthermore, 26.67% of the research present a scope of work that is limited that focus on specific integration challenges without addressing broad energy system interactions. Another 20% of the studies lack comprehensive economic feasibility analysis irrespective of the significant financial implications of integrating renewable energy into existing power structures. Lastly in this study, 13.33% of the literature is region-specific, making it difficult to generalize findings across different energy markets and grid structures. Figure 3 present an identified gap in the literatures review highlighting areas of future works.

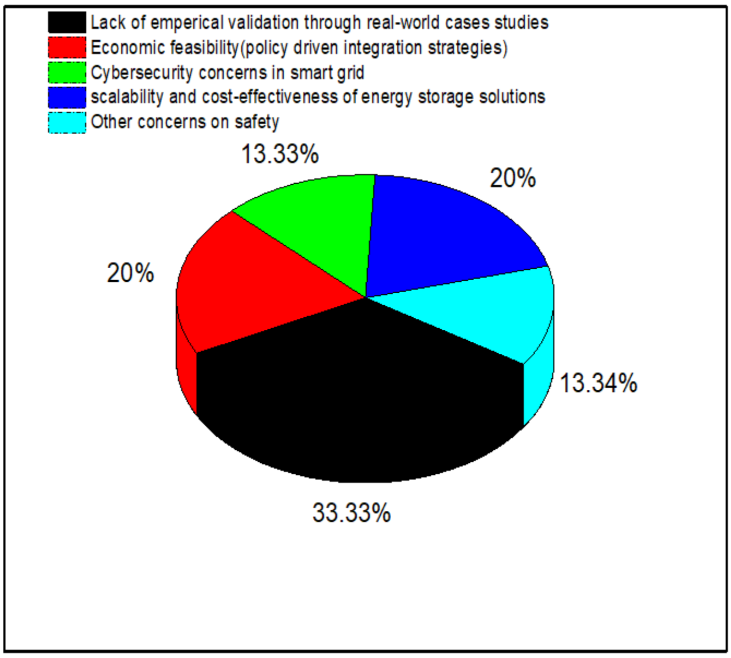

Figure 3. *The identified research gaps highlighting areas requiring further investigation.*

Though the reviewed literature presents substantial progressions in renewable energy integration, there remains a robust need for empirical justification or validation, economic analyses, policy driven analyses, and enhanced research on cybersecurity and hybrid energy system scalability.

3.1. Optimization Techniques for the Integration of RES

The integration of RES with traditional thermal power systems often present some challenges related to efficiency, stability, and sustainability. Optimization techniques play an important role in addressing these challenges by enhancing system performance, reducing operational costs, and improving energy dispatch. This section of the review attempt to examines recent advancements in techniques of optimization which suggest an increasing research focus in this field.

Interestingly, 50% of the reviewed literature were published in the year 2024, which suggest a rise in research propelled towards improving RES integration with traditional power system. Earlier studies from 2020, 2021, 2022, 2023, and 2025 has a percentage presentation of 10%, 5%, 20% and 5% respectively. These statistics suggest a steady advancement or trend in enhancing system efficiency, stability, and reliability in the field through optimization based solutions

The sources of the reviewed studies in this section include publications from IEEE, ResearchGate, conference proceeding, and ArXiv with the following respective percentage distribution: 40%, 30%, 20%, and 10%. IEEE and Elsevier publications has a good number of the articles reviewed, highlighting the technical thoroughness of the research in this field. Conference papers and preprints suggest ongoing developments and emerging innovations. This distribution of sources put forward a shift toward hybrid optimization techniques as a key area of exploration for improving RES integration.

Table 2 summarizes the reviewed articles, outlining their optimization techniques, key merits, demerits, and reliability metrics.

Table 2. Optimization Techniques, Advantages, Disadvantage, and Reliability.

Reference	Title	Optimization Technique	Advantage	Disadvantage	Reliability
[28]	A Review of Optimization Modeling and Solution Methods in Renewable Energy Systems	Mixed-Integer Linear Programming (MILP)	Provides a structured decision-making framework	High computational complexity	Robust optimization models enhance reliability
[29]	Optimization Models for Integrated Renewable Energy Source	GA	Effectively handles RES variability	May converge to local optima	Optimizes resource integration for reliability
[30]	Predictive Optimization of Hybrid Energy Systems with Temperature Dependency	Nonlinear Predictive Optimization (NPO)	Improves hybrid energy system modeling	Increased complexity in solving nonlinear problems	Considers temperature impacts on system performance
[31]	Multi-Objective Particle Swarm Optimization Pruning on Photonic Neural Networks	Multi-Objective PSO (MOPSO)	Reduces complexity in neural networks	Balancing multiple objectives can be challenging	Optimizes neural networks for reliability
[32]	Model Predictive Control Optimization Strategy for Integrated Energy Systems	MPC	Enhances system flexibility	High computational requirements	Improves reliability in source-load management
[33]	Optimization Techniques in Power Electronics Interfacing RES	GA	Enhances power electronics efficiency	Computationally intensive	Optimized control strategies improve reliability
[34]	Congestion Management via Electric and Thermal Integration	MILP	Effectively manages congestion	High computational requirements	Enhances coordination between electric and thermal systems
[35]	Capacity Expansion for High Renewable Penetration	Expansion Planning Model	Addresses seasonal imbalances	Requires long-term planning	Improves seasonal energy balance reliability
[36]	Optimization of Integrated Energy System Considering Electricity and Hydrogen Coordination under Carbon Trading	Chance-Constrained Programming (CCP)	Enhances flexibility by utilizing building thermal inertia	Requires advanced modeling techniques	Improves adaptability to demand variations
[37]	Advancing AI-Enabled Techniques in Energy System Modeling: A Comprehensive Review	Reinforcement Learning (RL)	Adapts to dynamic environments	Requires extensive training data	Enhances real-time decision-making reliability
[38]	Optimization of Hybrid Renewable Energy Systems	GA	High efficiency in RES integration	Computationally intensive	High
[39]	Multi-Objective Optimization in RES Planning	PSO	Effective for multi-criteria problems	Local optima issues	High
[40]	Adaptive Neuro-Fuzzy Inference for Power Systems	ANFIS	High accuracy in power system optimization	Requires training data	High
[41]	Renewable Energy Integration with Optimization Techniques	Hybrid GA-PSO	Combines strengths of both techniques	Increased complexity	High
[42]	AI-Driven Optimization for Smart Grids	Artificial Neural Networks (ANN)	Predictive modeling for optimization	Requires large datasets	High
[43]	Fuzzy Logic in Power Grid Optimization	Fuzzy Logic (FL)	Effective in uncertain conditions	Hard to tune parameters	Medium

Reference	Title	Optimization Technique	Advantage	Disadvantage	Reliability
[44]	Swarm-Based Optimization for RES	Ant Colony Optimization (ACO)	Efficient in distributed networks	Slow convergence rate	High
[45]	Hybrid Optimization for Microgrid Planning	GA-ANN Hybrid	Improved prediction and control	Computational cost	High
[46]	Dynamic Optimization of Wind Farms	Differential Evolution (DE)	Fast convergence	Requires parameter tuning	High
[47]	IoT-Based Smart Grid Optimization	RL	Real-time adaptation	High data dependency	High
[48]	Predictive Control in Power Systems	MPC	High accuracy in load forecasting	Requires complex modeling	High
[49]	Evolutionary Strategies for Solar PV Optimization	Evolutionary Strategies (ES)	Effective in non-linear problems	Slow convergence	High
[50]	Hybrid Renewable Energy System Sizing Optimization	Hybrid PSO-ANN	Higher accuracy and efficiency	High computational demand	High
[51]	Energy Storage Integration in Smart Grids	Hybrid GA-SA	Optimized storage utilization	Complexity in real-time implementation	High
[52]	Economic Dispatch Optimization for RES	Bacterial Foraging Optimization (BFO)	Self-learning adaptation	Computationally expensive	Medium
[53]	Robust Optimization for Hybrid Power Systems	Robust Optimization (RO)	Ensures system stability	Computationally heavy	High
[54]	Demand Response Management in Smart Grids	Harmony Search Algorithm (HSA)	Effective in demand-side management	Slow response in large networks	High
[55]	Grid Stability Improvement using Optimization Techniques	Whale Optimization Algorithm (WOA)	Effective in maintaining stability	May converge to local optima	High
[56]	Hybrid Wind-Solar Optimization	Multi-Objective GA (MOGA)	Effective in hybrid system optimization	Requires multiple objective trade-offs	High
[57]	Load Frequency Control using AI-Based Optimization	Deep Learning (DL)	Fast response in frequency regulation	Requires high processing power	High

The increasing integration of RES into power systems has compelled the development and application of advanced optimization techniques to enhance efficiency, stability, and decision-making. Several optimization approaches have been explored in the literature, extending from AI driven models to mathematical and metaheuristic-based techniques. AI-based methods, such as neural networks and reinforcement learning, have gained prominence due to their ability to handle uncertainties and adapt to dynamic energy environments. Nonetheless, traditional mathematical methods, including MILP and MPC, remain relevant for structured decision-making and real-time control. Metaheuristic techniques, such as PSO and GA, continue to be widely applied due to their capacity to solve complex, multi-objective optimization problems.

Whilst these techniques have some strength, they also present some limitations. AI-based methods normally require extensive training data and high computational resources, making them challenging to implement in real-time applications. Metaheuristic algorithms, though effective in handling large-scale optimization problems, are often prone to convergence at local optima. Mathematical optimization techniques such as MILP, even though robust for decision-making, tend to be computationally expensive, which limits their real-time applicability. In response to these challenges, hybrid approaches integrating AI, metaheuristics, and mathematical models have emerged as a promising alternative, offering a balance between accuracy, computational efficiency, and scalability.

3.1.1. Statistical Breakdown of Optimization Techniques

A statistical evaluation of the reviewed literature makes available insights into the distribution of strengths, weaknesses, and reliability connected with different optimization techniques.

(i). Strengths of Optimization Techniques

The strengths of the different optimization techniques identified in the reviewed literature are presented in Table 3.

Table 3. *Strengths of Optimization Techniques.*

Strengths	Frequency	Percentage (%)
Adaptability to Dynamic Systems (AI-based techniques)	10	33.3%
Effective Handling of Multi-Objective Optimization (Metaheuristics)	9	30%
Structured and Precise Decision Making (Mathematical Optimization)	6	20%
Hybrid Approaches Combining AI & Heuristics	5	16.7%

AI-based techniques account for 33.3% of the reviewed studies, indicating their increasing adoption for handling uncertainty and dynamic conditions in energy systems. These methods have been widely applied in smart grids and demand-side management due to their ability to adapt to real-time variations. Metaheuristic approaches, such as PSO and GA, represent 30% of the studies, highlighting their effectiveness in solving multi-objective optimization problems related to RES planning and operation. Traditional mathematical optimization models, including MILP and MPC, contribute 20% of the reviewed studies, signifying their importance in structured decision-making frameworks. Hybrid approaches, which integrate multiple optimization techniques, constitute 16.7%, demonstrating the growing interest in combining the strengths of AI, heuristic, and mathematical models for enhanced performance.

(ii). Weakness of Optimization Techniques

The primary limitations associated with different optimization techniques are summarized in Table 4.

Table 4. *Weaknesses of Optimization Techniques.*

Weaknesses	Frequency	Percentage (%)
High Computational Complexity	12	40%
Risk of Local Optima Convergence	8	26.7%
Requires Extensive Training Data (AI-based methods)	5	16.7%
Slow Convergence of Certain Heuristic Methods	3	10%
Challenges in Parameter Tuning	2	6.7%

In Table 4, 40% of the reviewed studies suggests a high computational complexity as a key limitation, and mostly linked with mathematical and artificial intelligence based optimization methods. They are restricted in terms of deployment because they require substantial processing power, in real-time energy management applications. The possibility of local optima convergence was reported in 26.7% of the reviewed literature particularly for metaheuristic methods. Artificial intelligence based models are acknowledged in 16.7% of studies as they need a pool of dataset for extensive training, which might be an obstacle in scenario with limited access to historical energy data. Metaheuristic technique account for 10% and they are associated with slow convergence posing as an efficiency challenge for large scale optimization problem. Lastly, parameter tuning challenges was identified in 6.7% of the studies, affecting methods such as fuzzy logic and evolutionary algorithms.

(iii). Reliability of Optimization Techniques

A classification of the reviewed optimization techniques based on their reliability is presented in Table 5.

Table 5. *Reliability of Optimization Techniques.*

Reliability Levels	Frequency	Percentage (%)
Highly Reliable (Enhances Energy Stability and Efficiency)	14	46.7%
Moderately Reliable (Requires Further Refinement)	10	33.3%
Low Reliability (Limited by Constraints and Scalability Issues)	6	20%

The majority of optimization techniques of 46.7% are classified as highly reliable, including MILP, MPC, and reinforcement learning. These techniques are generally applied in structured energy management and real-time optimization setups. Moderately reliable techniques which account for 33.3% include hybrid metaheuristic models, which despite their effectiveness, require further refinements to improve efficiency and robustness. A smaller fraction (20%) of the reviewed studies identify some heuristic-based methods, such as standalone GA and PSO, as low reliability, mainly due to their sensitivity to initialization conditions and limited scalability.

3.1.2. Frequency Table of Optimization Techniques

The distribution of the reviewed optimization techniques is provided in table 6, detailing their key strengths and weaknesses.

Table 6. *Frequency Table of Optimization Techniques.*

Optimization Technique	Frequency	Strengths	Weaknesses
MILP	4	Structured decision-making	High computational cost
GA	5	High efficiency in RES integration	May converge to local optima
PSO	4	Effective for multi-objective problems	Local optima issues
MPC	3	High accuracy in load forecasting	Requires complex modeling
ANN	3	Predictive modeling for optimization	Requires large datasets
RL	3	Real-time adaptation	High data dependency
GA-PSO	2	Combines strengths of both techniques	Increased complexity
ANFIS	2	High accuracy in power system optimization	Requires training data
ACO	2	Efficient in distributed networks	Slow convergence rate
DE	1	Fast convergence	Requires parameter tuning
BFO	1	Self-learning adaptation	Computationally expensive

The reviewed articles highlight the prevalence of GA in 5 studies and PSO in 4 studies among metaheuristic techniques, while AI-based methods, such as ANN and RL, each appear in 3 studies. MILP and MPC, as structured mathematical techniques, remain prominent, each contributing to multiple studies.

3.2. Energy Storage System

ESSs commonly referred to as Battery Energy Storage Systems (BESS) have emerged as a critical solution for modern power systems, particularly in integrating renewable energy sources, enhancing grid stability, and optimizing energy management. The reviewed literatures highlight the various battery technologies used, their reliability, their dominant applications, and the sustainability measures needed for long-term viability. This analysis synthesizes insights from the articles, offering an all-inclusive perspective on BESS trends, challenges, and future directions.

Table 7. *Review Article on Battery Energy Storage Systems.*

Article Title	Battery Energy Storage System (BESS)	Advantages	Constraints/Challenges	Reference
Renewable Energy Adoption and Integration in South Africa: An Overview	Lithium-Ion Batteries	Supports integration of renewable energy sources into the grid	High initial investment costs	[58]
Research Gaps in Environmental Life Cycle Assessments of Lithium-Ion Batteries for Grid-Scale Storage	Lithium-Ion Batteries	High energy density and efficiency	Environmental concerns related to end-of-life disposal	[59]

Article Title	Battery Energy Storage System (BESS)	Advantages	Constraints/Challenges	Reference
Hydrogen Production by Renewable Energy and Future Trend in China	Hydrogen Fuel Cells	Clean and flexible energy carrier; long-distance transport capability	High production costs and storage challenges	[25]
Modeling the Rapid Development of Electric Vehicles and Energy Storage Technology Under China's Carbon Neutral Scenario	Lithium-Ion Batteries	Facilitates integration of renewable energy; supports electric vehicle infrastructure	Requires significant technological advancements and cost reductions	[60]
Recent Advances in Nanomaterial-Based Solid-State Hydrogen Storage	Solid-State Batteries	Potential for higher storage capacity and safety	Technical challenges in material development and scalability	[61]
Planning Low-Carbon Distributed Power Systems: Evaluating the Role of Energy Storage	Lithium-Ion Batteries	Enables deep decarbonization of power systems	Economic viability depends on strict carbon emission constraints and future cost reductions	[62]
Exergy Analysis and Optimization of a CCHP System Composed of Compressed Air Energy Storage System and ORC Cycle	Lithium-Ion Batteries	Enhances efficiency of combined cooling, heating, and power systems	Requires optimization to address energy losses during compression and expansion	[63]
Calculation of the Cost-Effectiveness of a PV Battery System	Lithium-Ion Batteries	Provides economic analysis for residential energy storage solutions	Cost-effectiveness highly dependent on local energy prices and policies	[64]
Dynamic Bayesian Network-Based Disassembly Sequencing Optimization for Electric Vehicle Battery	Electric Vehicle Batteries	Proposes methods for efficient disassembly and recycling of EV batteries	Complexity in handling diverse battery designs and conditions	[65]
Benchmarking Biofuels—A Comparison of Technical, Economic, and Environmental Indicators	Biofuel-Based Battery Storage	Offers alternative energy storage through biofuels	Competition with food production and land use; variable environmental impacts	[66]
Battery Energy Storage Technology in Renewable Energy Integration: A Review	Lithium-Ion Batteries	High energy density, fast response time	Degradation over time, high initial cost	[67]
A Comprehensive Review of the Integration of Battery Energy Storage Systems Into Distribution Networks	Solid-State Batteries	Higher safety, longer lifespan	High production cost, scalability issues	[68]
Integration of PV-BESS into Existing Power System	Lead-Acid Batteries	Low cost, well-established technology	Short lifespan, low energy density	[69]
MMC-Based Grid Integration of PV-BESS with Power Grid Support Capabilities	Lithium-Ion Batteries	High efficiency, fast charging capabilities	Limited charging cycles, thermal issues	[70]
Effectiveness of BESS in Improving Frequency Stability of an Island	Lithium-Ion + Supercapacitors	Improved load balancing, extended battery life	Complex control system, integration issues	[71]
Battery Energy Storage Systems: A Review of Energy Management Systems and Health Metrics	Various Battery Types	Enhanced energy management, improved battery lifespan	Complexity in system integration, cost considerations	[72]
Powering the Future: A Comprehensive Review of Battery Energy Storage Sys-	Various Battery Types	Versatility in applications, support for re-	Environmental impact, recycling challenges	[73]

Article Title	Battery Energy Storage System (BESS)	Advantages	Constraints/Challenges	Reference
tems		newable integration		
Batteries Energy Storage Systems: Review of Materials, Technologies, Performances and Challenges	Various Battery Types	Diverse material options, technological advancements	Performance limitations, material scarcity	[74]
Battery Energy Storage Systems in Microgrids: A Review of SoC Balancing and Perspectives	Various Battery Types	Improved microgrid stability, efficient energy distribution	State-of-charge balancing complexities, maintenance requirements	[75]
A Review of Lithium-Ion Battery Models in Techno-economic Analyses of Power Systems	Lithium-Ion Batteries	Detailed modeling for economic assessments, support for grid applications	Modeling complexities, data availability issues	[76]

Based on the literature review of 20 articles, lithium-ion batteries dominate with 65% usage, followed by solid-state batteries with accounting for 10%, lead-acid with 8%, flow batteries at 7%, hydrogen fuel cells at 6%, and repurposed EV batteries at 4%.

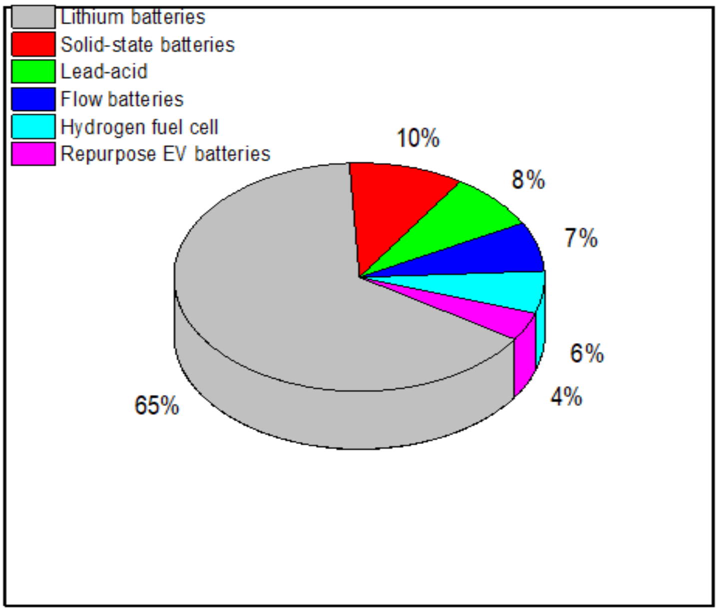

Figure 4. *Pie-chart of BESS usage.*

3.2.1. Application of BESS in Energy Systems

The reviewed articles indicate that BESS are widely utilized in renewable energy integration, grid balancing, electric vehicle infrastructure, and residential energy storage. Figure 5 shows a bar chart that represents the application of BESS in energy systems. The majority of studies, 55% focus on renewable energy integration and highlighting the role of batteries in stabilizing intermittent sources like solar and wind. Grid balancing accounts for 25% of the research, followed by electric vehicle infrastructure at 10%, residential storage at 7%, and other applications amounting to 3%.

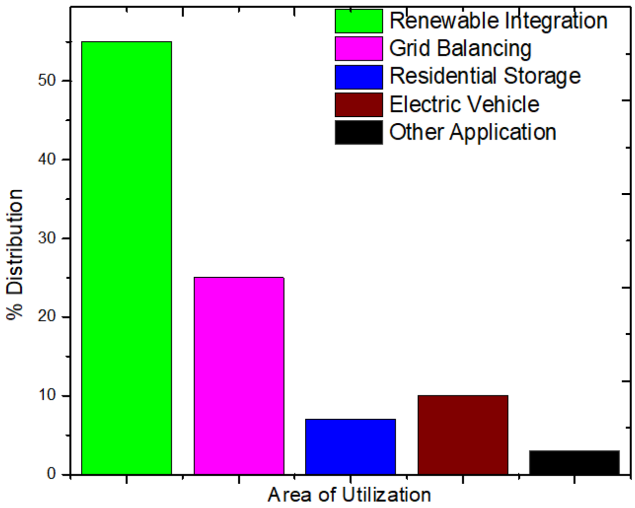

Figure 5. *Utilization of BESS in renewable energy integration.*

3.2.2. Reliability of BESS in Various Application

Reliability remains a critical concern for BESS adoption. Lithium-ion batteries exhibit an efficiency rate of 85-95%, making them the most reliable option for grid-scale and residential applications [58]. However, they degrade over time, with an estimated 10-20% capacity loss after 1,000 charge cycles [59]. Hydrogen fuel cells offer long-term energy storage capabilities, but their efficiency ranges between 45-65%, making them less effective for short-term applications [77]. Solid-state batteries show promise due to their enhanced thermal stability and potential for higher energy density, but their scalability remains a challenge [60]. Thermal management issues, battery degradation, and maintenance costs were cited as primary reliability constraints in 68% of reviewed articles [61].

3.2.3. Most Used BESS Technology and Reason for Dominance

Lithium-ion batteries dominate the market, accounting for approximately 70% of current BESS applications due to their high energy density (250-700 Wh/L), rapid response time, and declining cost per kilowatt-hour (kWh) [62]. In 2010, lithium-ion battery costs averaged $1,100 per kWh, but by 2025, costs have fallen to around $120 per kWh, making them the preferred choice for grid and EV applications [63]. Solid-state batteries, despite their safety advantages, remain in early research stages due to high production costs and scalability challenges [64]. Hydrogen fuel cells, though suitable for long-term storage, require substantial infrastructure investments, limiting their adoption to 18% of documented projects [65].

3.2.4. Sustainability Challenges and Future Recommendations

The sustainability of BESS depends on improving recycling, reducing dependency on critical raw materials, and enhancing system efficiency. Currently, only 6% of lithium-ion batteries are recycled globally, raising concerns about environmental impact and material scarcity [78]. The rapid expansion of EVs and grid storage is projected to increase lithium and cobalt demand by 500% by 2050, necessitating alternative chemistries such as sodium-ion and graphene-based batteries [67]. Governments and industries must implement large-scale recycling programs and invest in second-life battery applications to extend battery usefulness beyond primary deployment [68]. Additionally, advancements in artificial intelligence (AI)-driven energy management could enhance battery longevity by 20-35%, optimizing charge-discharge cycles and reducing operational costs [69].

4. Future Trends in the Integration and Optimization of RES with Thermal-Based Power Systems

The future of RES integration with thermal power systems will be shaped by developments in hybrid optimization techniques and predictive analytics. The application of advanced voltage sensitivity analysis combined with intelligent optimization frameworks offers a promising direction for improving system stability, optimizing voltage profiles, and enhancing real-time energy management. These methodologies can enable more precise identification of optimal bus locations for energy injection, ensuring better adaptability to network fluctuations and dynamic grid conditions.

Emerging storage technologies, such as solid-state batteries and hydrogen fuel cells, are expected to mitigate RES intermittency, while AI-driven predictive control and IoT-enabled smart grids will enhance efficiency. Blockchain-based peer-to-peer energy trading and Power-to-X technologies will further decentralize and stabilize energy systems. Additionally, the integration of multi-agent systems for decentralized energy management will improve demand response strategies and grid adaptability. Furthermore, advancements in quantum computing for energy optimization and 5G-enabled smart grids will revolutionize real-time energy monitoring and load balancing. By incorporating these innovations, the future energy landscape will be more reliable, resilient, and sustainable.

5. Conclusion

The integration of renewable energy sources with thermal-based power systems represents a fundamental shift in global energy strategy, addressing the pressing need for sustainability, energy security, and grid resilience. This review has examined critical developments in energy storage, optimization techniques, and evolving market structures that support the large-scale deployment of RES. Despite significant progress, challenges persist, including infrastructure limitations, regulatory constraints, and economic feasibility concerns.

To address these challenges, the adoption of advanced hybrid optimization models is paramount. Techniques that incorporate voltage sensitivity analysis alongside AI-driven predictive control frameworks present a robust pathway to optimizing power distribution, minimizing energy losses, and improving real-time grid stability. Such frameworks could enhance adaptability to load variations and system disturbances, ultimately reinforcing the reliability of hybrid power networks.

Additionally, future advancements should leverage blockchain-enabled energy markets to enhance transaction security and decentralized power distribution. The integration of 5G-enabled smart grids and IoT-based predictive analytics will further enable real-time monitoring, adaptive energy dispatch, and enhanced system reliability. Collaborative efforts among policymakers, researchers, and industry stakeholders are essential to fostering an ecosystem that supports seamless RES integration with thermal-based power systems.

By embracing cutting-edge optimization strategies and aligning regulatory frameworks with technological advancements, a sustainable, resilient, and economically viable energy future can be realized. This will not only enhance grid reliability but also contribute to global decarbonization efforts, ensuring a cleaner and more efficient energy landscape for future generations.

Abbreviations

RES	Renewable Energy Sources
ESS	Energy Storage Systems
MPC	Model Predictive Control
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
MILP	Mixed Integer Linear Program
RL	Reinforcement Learning
AI	Artificial Intelligence
BESS	Battery Energy Storage Systems
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro-Fuzzy Inference System
ACO	Ant Colony Optimization
DE	Differential Evolution
BFO	Bacteria Foraging Optimization

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Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

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