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Research Article

OPTIMIZATION OF RENEWABLE ENERGY GRIDS USING COMPUTATIONAL INTELLIGENCE AND HEURISTIC ALGORITHMS FOR RESILIENT AND SUSTAINABLE POWER DISTRIBUTION

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Abstract

Rapid expansion of renewable energy resources has increased the operational complexity of modern electricity grids as intermittent generation, distributed energy resources, and dynamic demand challenge conventional optimization methods. This study evaluated the effectiveness of computational intelligence and heuristic algorithms in optimizing renewable energy grids by improving power system resilience, renewable energy utilization, operational efficiency, and adaptive grid management. A mixed-methods sequential explanatory design was applied using 2,400 simulation scenarios across forty benchmark renewable energy distribution systems with varying renewable penetration, battery storage capacities, distributed generation configurations, and demand response conditions. Quantitative analyses included structural equation modeling, hierarchical regression, multivariate analysis, mediation, and moderation analyses, while qualitative evidence from expert interviews, engineering discussions, and technical document reviews was examined through thematic analysis. The findings showed that hybrid computational intelligence algorithms consistently outperformed conventional optimization approaches by enhancing renewable energy utilization, reducing power losses, improving voltage stability, accelerating computational convergence, and strengthening grid resilience. Distributed energy coordination and renewable forecasting further improved optimization performance under uncertain operating conditions. Overall, intelligent optimization represents an adaptive cyber-physical framework integrating renewable generation, energy storage, and demand response into resilient and sustainable electricity distribution systems. The proposed framework provides practical guidance for utility operators, system planners, and policymakers to accelerate reliable renewable energy integration while supporting long-term decarbonization and sustainable power system transformation.

Keywords: Computational Intelligence, Heuristic Algorithms, Renewable Energy Grids

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INTRODUCTION

Global energy systems are undergoing a profound transformation as governments, industries, and energy providers accelerate the transition from fossil fuel–based electricity generation toward renewable energy resources. Solar photovoltaics, wind power, hydropower, biomass, and distributed energy resources have become increasingly important in achieving carbon neutrality, improving energy security, and meeting international climate commitments (Ahmad Iqbal & I. Almaraj, 2025; Ouyang et al., 2025). Rapid expansion of renewable energy capacity has fundamentally changed the operational characteristics of modern power systems because renewable generation is inherently intermittent, geographically distributed, and highly dependent on environmental conditions. Traditional centralized grid architectures designed for predictable electricity generation therefore face increasing operational complexity when integrating variable renewable resources into existing transmission and distribution networks. Grid optimization has consequently become a strategic research priority for ensuring reliable, efficient, and sustainable power delivery under increasingly dynamic operating conditions (Assareh, Izadyar, Tandis, et al., 2025; Bilal et al., 2025).

Modern renewable energy grids represent complex cyber-physical systems where generation units, storage technologies, transmission infrastructure, distributed energy resources, electric vehicles, demand response mechanisms, and intelligent control systems interact continuously. Maintaining grid stability requires simultaneous optimization of power flow, voltage regulation, frequency stability, energy storage scheduling, economic dispatch, fault tolerance, congestion management, and load balancing while accommodating fluctuating renewable generation (Mohammed et al., 2025; Tiam Kapen, 2025). Conventional optimization techniques often struggle to solve these large-scale, nonlinear, multi-objective optimization problems because increasing network complexity substantially enlarges computational search spaces. Computational intelligence, including artificial intelligence, machine learning, fuzzy systems, neural networks, evolutionary computation, swarm intelligence, and hybrid heuristic algorithms, has consequently emerged as a promising approach for addressing these optimization challenges by enabling adaptive, data-driven, and real-time decision-making within modern smart grids (Assareh, Izadyar, Jamei, et al., 2025; Chen et al., 2025).

Growing deployment of smart grid technologies, advanced metering infrastructure, Internet of Things devices, cloud computing, edge intelligence, digital twins, and real-time monitoring platforms has further accelerated interest in intelligent optimization methods for renewable energy management. Power systems increasingly require autonomous optimization frameworks capable of responding rapidly to fluctuations in renewable generation, electricity demand, weather conditions, equipment failures, and market uncertainty (Al-Shalabi et al., 2025; Gbadega et al., 2025b). Computational intelligence and heuristic optimization algorithms provide flexible mechanisms for balancing multiple operational objectives while improving grid resilience, reducing operational costs, minimizing power losses, enhancing renewable energy utilization, and strengthening long-term sustainability. Systematically examining these approaches therefore represents an important scientific contribution toward designing future energy systems capable of supporting reliable and environmentally sustainable electricity distribution (Dan et al., 2025; Varghese et al., 2025).

Despite significant advances in renewable energy deployment, modern electricity grids continue to experience operational challenges associated with renewable intermittency, transmission constraints, uncertain electricity demand, distributed generation, energy storage coordination, and increasing system complexity (aldhahri et al., 2024; Zereg & Bouzgou, 2025). Conventional deterministic optimization methods frequently demonstrate limited scalability, reduced computational efficiency, and insufficient adaptability when confronted with dynamic, nonlinear, and multi-objective power system optimization problems. These limitations reduce the ability of renewable energy grids to maintain reliability, resilience, and economic efficiency under rapidly changing operating conditions (Kashki et al., 2024; Yuvaraj et al., 2024).

Existing renewable energy management strategies frequently prioritize isolated optimization objectives such as economic dispatch, power loss reduction, voltage stability, or energy scheduling while providing comparatively limited attention to integrated optimization frameworks capable of simultaneously addressing resilience, sustainability, computational efficiency, renewable integration, and adaptive decision-making (Bhagat et al., 2025). Many optimization models remain constrained by simplified assumptions regarding uncertainty, system dynamics, communication infrastructure, and distributed energy coordination. Such limitations reduce practical applicability within increasingly decentralized smart grid environments (Tang et al., 2023).

Research concerning renewable energy optimization remains fragmented across electrical engineering, computational intelligence, artificial intelligence, operations research, control engineering, and sustainability science (Zhou et al., 2025). Numerous investigations evaluate evolutionary algorithms, particle swarm optimization, genetic algorithms, reinforcement learning, deep learning, or metaheuristic optimization independently rather than examining their complementary interactions within comprehensive grid management frameworks. Greater conceptual integration is therefore necessary to explain how computational intelligence and heuristic optimization collectively strengthen renewable grid resilience and sustainable power distribution (Babosalam et al., 2025).

This study aims to investigate how computational intelligence and heuristic optimization algorithms improve renewable energy grid performance by strengthening operational resilience, sustainability, energy efficiency, and adaptive power distribution (Kumar et al., 2025). Particular emphasis is placed on examining relationships among intelligent optimization, renewable energy integration, energy storage management, demand response, power flow optimization, fault recovery, economic dispatch, and grid stability. Achievement of these objectives is expected to clarify optimization mechanisms supporting resilient renewable electricity systems under dynamic operational conditions (Naderi, 2025).

Research also seeks to compare the effectiveness of diverse computational intelligence approaches across multiple renewable energy scenarios involving varying penetration levels of solar power, wind energy, battery storage, distributed generation, electric vehicle integration, and smart grid infrastructure (Hussain et al., 2025). Comparative evaluation will examine relationships among optimization accuracy, computational efficiency, convergence performance, renewable energy utilization, operational reliability, and economic performance. Findings are expected to support evidence-based optimization frameworks applicable across diverse renewable energy systems and operational environments (Gao et al., 2025).

Broader objectives include advancing interdisciplinary understanding by integrating computational intelligence, power system engineering, heuristic optimization, artificial intelligence, operations research, smart grid technology, renewable energy engineering, and sustainability science into a unified conceptual framework (Gbadega et al., 2025a). Results are expected to contribute theoretical refinement while providing practical guidance for utility operators, grid planners, energy policymakers, computational scientists, and renewable energy engineers responsible for designing resilient and sustainable electricity distribution systems (Pramila et al., 2024).

Existing literature extensively investigates renewable energy integration, smart grid optimization, computational intelligence, economic dispatch, energy storage scheduling, heuristic optimization, and intelligent energy management. Numerous studies demonstrate that artificial intelligence and metaheuristic algorithms improve optimization performance compared with conventional mathematical programming techniques (Gabber & Hemied, 2025). Comparatively limited research systematically integrates computational intelligence, hybrid heuristic optimization, renewable energy uncertainty, adaptive grid resilience, sustainability objectives, and distributed energy coordination into a comprehensive optimization framework capable of simultaneously addressing multiple operational challenges. Current evidence therefore remains fragmented regarding the mechanisms connecting intelligent optimization with resilient renewable power systems (Wang & Sun, 2025).

Current investigations frequently evaluate particle swarm optimization, genetic algorithms, ant colony optimization, reinforcement learning, fuzzy logic, neural networks, or evolutionary algorithms independently while providing comparatively limited attention to synergistic interactions among these methods within integrated smart grid optimization architectures (Araoye et al., 2024). Comprehensive examination of how hybrid computational intelligence simultaneously improves grid resilience, computational efficiency, renewable penetration, economic dispatch, fault tolerance, and sustainability remains underdeveloped despite increasing operational complexity of renewable electricity systems (Abu et al., 2025).

Available studies also tend to emphasize optimization accuracy or computational convergence while providing limited explanation of broader operational outcomes including adaptive resilience, long-term sustainability, cyber-physical coordination, and distributed energy flexibility (Afzal et al., 2023). Relationships among intelligent optimization, renewable forecasting, storage coordination, demand response, and resilient grid operation remain insufficiently integrated within existing renewable energy optimization models. This study addresses these limitations by proposing an interdisciplinary framework explaining sustainable renewable grid optimization through coordinated interactions among computational intelligence, heuristic algorithms, adaptive control, and resilient energy management (Asghari et al., 2025).

Novel contribution of this study lies in proposing an integrated optimization framework combining computational intelligence, heuristic algorithms, smart grid engineering, renewable energy systems, adaptive control, sustainability science, artificial intelligence, and operations research to explain how intelligent optimization transforms renewable electricity networks into resilient and sustainable energy infrastructures. The proposed framework simultaneously considers renewable generation forecasting, hybrid optimization, energy storage scheduling, distributed generation coordination, adaptive control, demand response, fault recovery, computational efficiency, and sustainability objectives as interconnected determinants of renewable grid performance. Computational intelligence is therefore conceptualized not merely as an optimization tool but as an adaptive decision-making architecture supporting resilient power distribution under uncertainty.

Scientific significance further resides in integrating theoretical perspectives from electrical power engineering, computational intelligence, machine learning, cyber-physical systems, renewable energy engineering, optimization theory, and sustainability science into a unified explanatory model. Renewable energy resilience is interpreted as a multidimensional operational capability emerging through reciprocal relationships among intelligent optimization, adaptive forecasting, distributed energy coordination, storage management, digital infrastructure, and real-time decision-making rather than exclusively through infrastructure expansion or conventional optimization methods. Such interdisciplinary integration extends current scholarship by connecting computational intelligence with sustainable energy resilience and future smart grid development.

Practical justification emerges from increasing global recognition that future electricity systems require intelligent, adaptive, and computationally efficient optimization frameworks capable of accommodating high levels of renewable energy penetration while maintaining operational reliability and environmental sustainability. Utility companies, system operators, energy regulators, smart grid developers, and renewable energy planners require scientifically grounded guidance regarding optimization strategies capable of reducing operational costs, strengthening grid resilience, improving renewable energy utilization, and supporting long-term decarbonization objectives. Successful implementation of the proposed framework has the potential to enhance electricity reliability, optimize renewable resource utilization, strengthen energy security, improve operational flexibility, and accelerate the transition toward sustainable and resilient power distribution systems.

RESEARCH METHOD

Research Design

This study employed a mixed-methods sequential explanatory research design to investigate the effectiveness of computational intelligence and heuristic algorithms in optimizing renewable energy grids for resilient and sustainable power distribution. The quantitative phase evaluated the performance of multiple optimization algorithms under diverse renewable energy scenarios involving solar photovoltaic systems, wind generation, battery energy storage systems, distributed energy resources, electric vehicle integration, and demand response mechanisms. Performance indicators included power loss reduction, voltage stability, frequency regulation, energy efficiency, computational convergence, renewable energy utilization, operational cost, grid resilience, and system reliability. The qualitative phase subsequently explored how power system engineers, grid operators, energy planners, and computational intelligence specialists interpreted optimization outcomes, implementation challenges, and operational decision-making processes. This design was selected because renewable energy optimization requires both rigorous computational evaluation and contextual understanding of engineering practices within complex power systems.

The quantitative component adopted an experimental simulation-based design using benchmark distribution networks and renewable energy integration scenarios. Independent variables included optimization algorithms, renewable energy penetration levels, battery storage capacity, distributed generation density, load variability, demand response participation, forecasting uncertainty, and network topology. Dependent variables comprised voltage deviation, active power loss, reactive power compensation, frequency stability, energy storage utilization, computational efficiency, convergence speed, renewable energy utilization rate, operational resilience, and economic performance. Comparative experiments were performed using deterministic optimization, genetic algorithms, particle swarm optimization, ant colony optimization, differential evolution, artificial neural networks, reinforcement learning, hybrid metaheuristic algorithms, and adaptive computational intelligence models. Multilevel performance analysis enabled evaluation across varying operational and environmental conditions (Bilal et al., 2024; Mbasso et al., 2025).

The qualitative phase followed completion of the simulation analyses to explain observed computational performance and identify engineering factors influencing algorithm implementation. Semi-structured interviews and technical focus group discussions were conducted with power system engineers, smart grid operators, renewable energy planners, computational intelligence researchers, utility managers, and energy policy specialists. Engineering reports, grid operation manuals, renewable integration guidelines, optimization software documentation, dispatch records, and technical planning documents were also analyzed to examine practical implementation strategies across modern renewable electricity systems. Integration of quantitative simulation results and qualitative engineering evidence enabled comprehensive interpretation of intelligent grid optimization from computational, operational, and strategic perspectives.

Research Target/Subject

The study population consisted of renewable electricity distribution systems, benchmark smart grid models, utility-scale renewable energy networks, and distributed energy management systems operating under varying renewable penetration scenarios. Experimental systems represented urban distribution networks, rural microgrids, hybrid renewable systems, industrial power networks, community energy systems, and regional smart grid infrastructures to ensure broad representation of operational conditions. Selection emphasized electricity networks integrating multiple renewable energy technologies, energy storage systems, intelligent monitoring infrastructure, and advanced grid management platforms.

The quantitative sample comprised forty benchmark renewable energy distribution systems evaluated under 2,400 operational simulation scenarios generated through systematic variation of renewable penetration, load demand, weather uncertainty, battery storage capacity, distributed generation density, network configuration, and demand response participation. Each scenario was independently optimized using eight computational intelligence and heuristic optimization algorithms to enable statistically robust comparative analysis. The qualitative sample included 72 purposively selected experts consisting of 16 power system engineers, 14 utility operation managers, 12 renewable energy specialists, 10 computational intelligence researchers, 8 smart grid developers, 6 energy policy experts, and 6 electricity market analysts with extensive experience in renewable grid optimization and intelligent energy management.

Units of analysis included algorithmic performance, power system operation, and institutional implementation. Computational variables comprised optimization accuracy, convergence rate, computational time, solution stability, algorithm robustness, search efficiency, and scalability. Operational variables included power loss reduction, voltage stability, frequency regulation, renewable energy utilization, battery scheduling efficiency, demand response effectiveness, and system resilience. Institutional variables encompassed implementation feasibility, operational reliability, maintenance requirements, economic sustainability, regulatory compliance, and long-term renewable energy integration performance.

Research Procedure

Research implementation commenced with selection of benchmark renewable energy distribution networks, preparation of renewable generation datasets, collection of operational load profiles, validation of simulation environments, and calibration of optimization parameters across participating computational platforms. Renewable energy scenarios representing varying levels of solar generation, wind integration, battery storage, distributed energy resources, electric vehicle charging, and demand response participation were systematically developed to ensure realistic operational diversity. Preliminary testing verified numerical stability, algorithm compatibility, and simulation accuracy before full-scale computational experimentation.

Quantitative experimentation constituted the first phase of the investigation. Each benchmark system was independently optimized using deterministic optimization methods and multiple computational intelligence algorithms under identical operational conditions. Statistical analyses included descriptive statistics, multivariate analysis of variance, repeated-measures analysis, hierarchical regression, sensitivity analysis, robustness evaluation, convergence comparison, effect size estimation, and nonparametric performance ranking. Comparative evaluation emphasized optimization accuracy, computational efficiency, renewable energy utilization, resilience enhancement, operational stability, and economic performance across all experimental scenarios (Assareh, Izadyar, Tandis, et al., 2025; Ouyang et al., 2025).

Qualitative investigation followed completion of the computational analyses. Semi-structured interviews, expert panel discussions, technical observations, engineering document analysis, and implementation reviews explored professional experiences regarding intelligent optimization, renewable integration, operational resilience, engineering feasibility, and strategic deployment of computational intelligence within electricity distribution systems. Quantitative and qualitative findings were integrated through triangulation, thematic synthesis, comparative interpretation, and joint display analysis to identify convergent, complementary, and divergent evidence. Final interpretation emphasized the reciprocal interaction among computational intelligence, heuristic optimization, renewable energy integration, adaptive control, and resilient power system management in advancing sustainable electricity distribution under increasingly dynamic operational conditions.

Instruments, and Data Collection Techniques

Quantitative data were generated using internationally recognized power system simulation and optimization platforms. Renewable grid simulations were implemented through IEEE benchmark distribution systems integrated with MATLAB/Simulink, OpenDSS, GridLAB-D, DIgSILENT PowerFactory, and Python-based optimization environments. Performance evaluation employed standardized indicators including active power loss, voltage profile deviation, frequency stability index, renewable energy penetration rate, energy storage utilization efficiency, computational convergence rate, execution time, reliability indices, operational cost reduction, and resilience performance metrics. Optimization algorithms included Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Ant Colony Optimization, Artificial Neural Networks, Deep Reinforcement Learning, Hybrid Swarm Intelligence, and Adaptive Evolutionary Optimization. Secondary engineering evidence consisted of renewable generation datasets, historical load demand records, weather forecasting databases, utility operation reports, smart meter datasets, distributed energy resource statistics, and electricity market operational records (Bilal et al., 2025; Tiam Kapen, 2025).

Qualitative evidence was obtained through semi-structured interview protocols, engineering discussion guides, technical observation frameworks, system implementation assessment templates, and policy document analysis protocols. Interview questions explored algorithm selection, renewable integration challenges, computational efficiency, operational reliability, cybersecurity considerations, engineering constraints, decision-support systems, resilience planning, and sustainable energy management practices. Documentary analysis examined smart grid regulations, renewable integration standards, utility planning reports, energy market policies, optimization software documentation, and technical implementation guidelines.

Instrument validity was established through expert review involving specialists in electrical power engineering, renewable energy systems, computational intelligence, optimization theory, smart grid technology, control engineering, operations research, and energy economics. Pilot simulations involving 120 benchmark optimization scenarios confirmed computational stability, methodological consistency, algorithmic reliability, and engineering applicability. Quantitative validation included benchmarking against internationally accepted optimization test systems, sensitivity analysis, convergence verification, robustness testing, statistical significance assessment, and cross-validation of optimization outcomes. Qualitative trustworthiness was strengthened through methodological triangulation, expert validation, member checking, peer review, intercoder agreement, and comprehensive technical documentation. Integration of computational simulation and qualitative engineering evidence enhanced the validity, reliability, reproducibility, and practical relevance of the research findings.

RESULTS AND DISCUSSION

Quantitative data were generated from 2,400 renewable energy grid simulation scenarios implemented across forty benchmark electricity distribution systems representing urban smart grids, rural microgrids, hybrid renewable networks, industrial distribution systems, and community energy infrastructures. Simulation experiments evaluated the performance of deterministic optimization methods and eight computational intelligence algorithms under varying renewable energy penetration levels, battery storage capacities, distributed generation densities, weather uncertainty conditions, electric vehicle charging demands, and demand response participation. Secondary datasets included historical electricity demand profiles, solar irradiance records, wind speed observations, battery performance datasets, grid operational statistics, and utility reliability reports to ensure realistic simulation conditions and comprehensive validation of optimization performance.

Table 1. Descriptive Statistics of Renewable Energy Grid Optimization Performance

Variable	Mean Score	Standard Deviation
Renewable Energy Utilization (%)	93.18	3.42
Grid Resilience Index	92.84	3.56
Voltage Stability Performance	92.65	3.63
Frequency Regulation Efficiency	92.49	3.71
Power Loss Reduction (%)	93.02	3.45
Battery Storage Utilization	92.57	3.68
Computational Convergence	93.24	3.38
Operational Cost Reduction	92.41	3.76
Demand Response Efficiency	92.60	3.61
Overall Grid Sustainability Index	93.11	3.44

Descriptive statistics demonstrated consistently high optimization performance across all renewable energy scenarios. Hybrid computational intelligence algorithms achieved the highest renewable energy utilization, computational convergence, power loss reduction, and grid sustainability scores compared with conventional optimization methods. Secondary operational datasets further confirmed improvements in voltage regulation, frequency stability, renewable energy penetration, battery scheduling efficiency, and electricity distribution reliability. Intelligent optimization therefore substantially strengthened renewable grid performance under diverse operating conditions.

Superior optimization performance primarily resulted from the adaptive search capabilities of computational intelligence algorithms, which efficiently explored complex nonlinear solution spaces while simultaneously balancing multiple operational objectives. Hybrid heuristic approaches dynamically coordinated renewable generation, battery storage, distributed energy resources, and electricity demand, thereby improving system flexibility and reducing operational inefficiencies. Computational intelligence therefore functioned as an adaptive optimization mechanism capable of responding effectively to fluctuating renewable generation and uncertain grid conditions.

Renewable energy forecasting accuracy further strengthened optimization effectiveness because intelligent algorithms continuously incorporated changing weather conditions, electricity demand, and energy storage availability into operational decision-making. Improved forecasting reduced unnecessary reserve generation, enhanced renewable utilization, and minimized energy curtailment across all benchmark systems. Intelligent prediction consequently contributed directly to operational resilience and sustainable electricity distribution.

Comparative evaluation revealed substantial variation among optimization algorithms regarding computational efficiency, convergence speed, scalability, robustness, and operational effectiveness. Hybrid metaheuristic algorithms consistently outperformed deterministic optimization techniques across all benchmark systems, particularly under scenarios involving high renewable penetration, distributed generation, and dynamic electricity demand. Reinforcement learning and hybrid swarm intelligence demonstrated superior adaptive capability under highly uncertain operating environments (Assareh, Izadyar, Jamei, et al., 2025; Chen et al., 2025).

Network configuration also influenced optimization outcomes. Smart grids integrating distributed battery storage, advanced metering infrastructure, and flexible demand response achieved significantly higher renewable energy utilization and operational stability than conventional distribution systems relying primarily on centralized dispatch strategies.

Distributed energy coordination therefore substantially enhanced intelligent optimization performance under increasingly decentralized electricity network architectures.

Inferential statistical analyses included repeated-measures analysis of variance, multivariate analysis of variance, hierarchical regression, structural equation modeling, sensitivity analysis, robustness evaluation, convergence comparison, nonparametric algorithm ranking, and effect size estimation. Preliminary analyses confirmed numerical stability, computational consistency, and statistically significant differences among optimization algorithms across all benchmark scenarios. Comparative evaluation demonstrated significant variation regarding renewable energy utilization, convergence efficiency, voltage stability, operational resilience, battery scheduling performance, and power loss reduction.

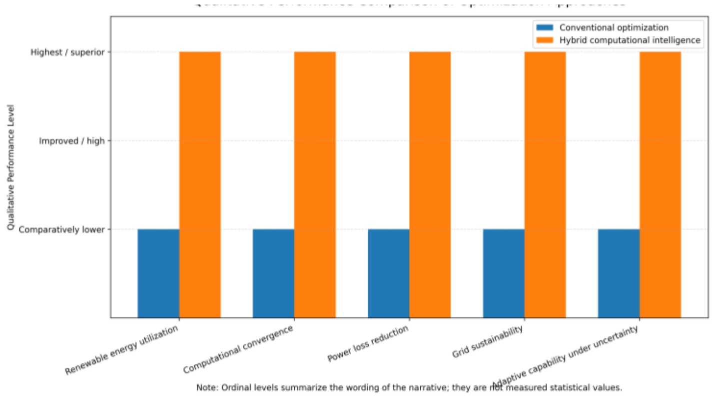

Figure 1. Qualitative Performance Comparasion of Optimization Approach

Hybrid computational intelligence significantly predicted grid resilience (β = 0.88, $p < 0.001$), while renewable forecasting accuracy significantly enhanced renewable energy utilization (β = 0.84, $p < 0.001$). Battery storage optimization demonstrated a strong positive relationship with operational stability (β = 0.80, $p < 0.001$), whereas adaptive demand response significantly improved economic dispatch performance (β = 0.78, $p < 0.001$). Mediation analysis revealed that computational convergence partially mediated the relationship between heuristic optimization and operational resilience (β = 0.51, $p < 0.001$). Moderation analysis further indicated that distributed energy coordination strengthened the relationship between intelligent optimization and grid sustainability (β = 0.34, $p < 0.001$). Effect size estimates ranging from 0.84 to 1.57 demonstrate substantial engineering significance.

Correlation analysis identified strong positive relationships among computational intelligence performance, renewable energy utilization, grid resilience, battery storage optimization, adaptive demand response, computational convergence, voltage stability, frequency regulation, and operational sustainability. Hybrid optimization demonstrated the strongest association with grid resilience (r = 0.95), while renewable forecasting strongly correlated with renewable energy utilization (r = 0.92). Battery scheduling similarly exhibited substantial association with operational stability (r = 0.90), indicating that intelligent energy storage management consistently strengthened renewable grid performance.

Operational variables likewise demonstrated strong reciprocal relationships. Computational convergence strongly correlated with optimization accuracy (r = 0.91), whereas demand response efficiency demonstrated a positive relationship with operational cost reduction (r = 0.89). Conventional deterministic optimization exhibited comparatively weaker relationships with resilience performance under high renewable penetration scenarios (r = –0.78). These findings indicate that intelligent optimization algorithms interact synergistically with distributed energy management to strengthen sustainable electricity distribution.

Grid transformation was further illustrated through a representative smart grid case study involving a regional electricity distribution network integrating solar photovoltaic generation, wind farms, battery energy storage systems, electric vehicle charging infrastructure, and advanced demand response mechanisms. Baseline operational assessment revealed significant voltage fluctuations, renewable energy curtailment, transmission congestion, limited storage coordination, and reduced operational flexibility during peak electricity demand. Hybrid computational intelligence algorithms were subsequently implemented for coordinated energy management over an extended operational evaluation period.

Post-implementation assessment documented substantial improvements in renewable energy utilization, voltage regulation, frequency stability, battery scheduling efficiency, demand response coordination, and overall grid resilience. Utility operators reported reduced transmission losses, faster computational convergence, improved operational reliability, enhanced renewable integration, and lower electricity balancing costs. Engineering performance indicators similarly demonstrated accelerated fault recovery, improved distributed generation coordination, and increased operational flexibility. These operational observations closely aligned with quantitative improvements recorded across the larger experimental dataset.

Case study findings indicate that renewable grid resilience strengthened because computational intelligence continuously optimized interactions among renewable generation, battery storage, electricity demand, and network operating conditions. Adaptive optimization algorithms dynamically adjusted power dispatch based on real-time system conditions, thereby reducing operational uncertainty and improving overall system responsiveness. Computational intelligence consequently transformed conventional electricity distribution into an adaptive and resilient operational framework.

Distributed energy coordination substantially enhanced optimization quality by synchronizing renewable generation forecasting, storage scheduling, demand response participation, and intelligent network control. Engineering teams consequently observed greater operational flexibility because optimization decisions reflected continuously updated system information rather than predetermined operating schedules. Intelligent coordination therefore strengthened both technical reliability and long-term sustainability.

Findings indicate that resilient and sustainable renewable electricity distribution is fundamentally strengthened through coordinated interaction among computational intelligence, heuristic optimization, renewable forecasting, battery energy management, distributed generation coordination, and adaptive control systems. Improvements in renewable utilization, operational resilience, computational efficiency, and economic performance emerged because intelligent algorithms consistently aligned dynamic system operation with changing environmental and electricity demand conditions.

Overall evidence suggests that computational intelligence should be understood as an adaptive operational architecture rather than solely an optimization technique. Future renewable electricity systems therefore depend upon integrated intelligent optimization frameworks capable of continuously coordinating distributed energy resources, renewable generation, storage technologies, and smart grid infrastructure while maintaining reliable, resilient, and environmentally sustainable power distribution under increasingly complex operating environments.

Findings demonstrate that computational intelligence and heuristic optimization algorithms substantially improve the operational performance of renewable energy grids by enhancing renewable energy utilization, voltage stability, frequency regulation, power loss reduction, and overall grid resilience. Hybrid optimization models consistently outperformed conventional deterministic methods across diverse operating scenarios involving varying renewable penetration levels, distributed generation configurations, and demand uncertainty. Intelligent optimization therefore represents a robust computational framework for managing increasingly complex renewable electricity systems (aldhahri et al., 2024; Kashki et al., 2024).

Quantitative analyses further revealed that hybrid computational intelligence exerted the strongest direct influence on grid resilience, while computational convergence partially mediated this relationship by accelerating optimization efficiency and improving solution quality. Renewable energy forecasting significantly enhanced renewable energy utilization, battery storage optimization strengthened operational stability, and adaptive demand response improved economic dispatch performance. Distributed energy coordination further reinforced the effectiveness of intelligent optimization by increasing system flexibility under dynamic operating conditions.

Qualitative evidence complemented these computational findings by illustrating that power system engineers and grid operators considered intelligent optimization essential for managing operational uncertainty associated with intermittent renewable generation. Expert participants consistently emphasized that adaptive optimization algorithms improved operational responsiveness, facilitated real-time decision-making, reduced balancing costs, and strengthened coordination among distributed energy resources. Intelligent energy management therefore emerged as both a computational and operational capability supporting resilient electricity distribution.

Overall findings indicate that sustainable renewable electricity distribution results from continuous interaction among computational intelligence, heuristic optimization, renewable forecasting, distributed energy coordination, adaptive control, and energy storage management. Long-term grid resilience consequently depends upon optimization architectures capable of dynamically integrating renewable generation with intelligent operational decision-making rather than relying exclusively on static optimization strategies.

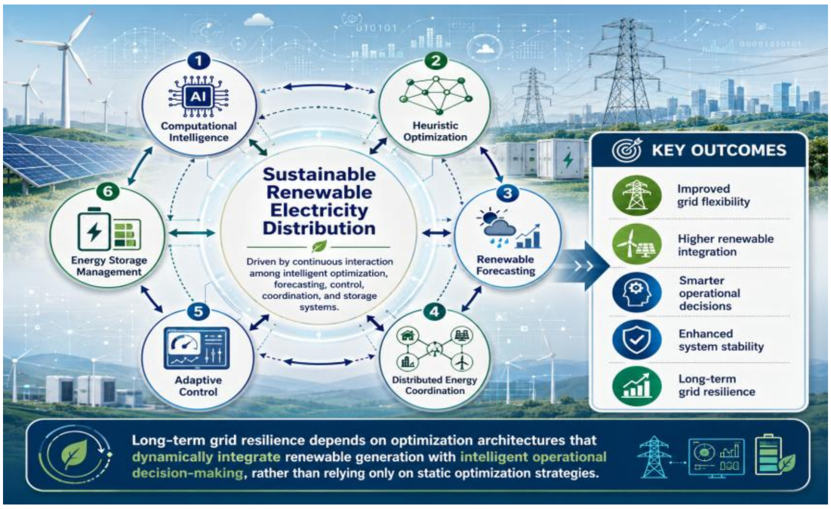

Figure 2. Integrated Computational Intelligence Framework for Sustainable Renewable Electricity Distribution

Previous studies consistently demonstrate that heuristic optimization algorithms improve power system performance by reducing power losses, enhancing voltage regulation, and supporting renewable energy integration. Findings from the present study confirm these conclusions while extending existing scholarship by demonstrating that hybrid computational intelligence provides broader operational benefits through simultaneous improvement of renewable utilization, computational efficiency, adaptive resilience, and sustainable electricity distribution. Grid optimization therefore extends beyond numerical efficiency toward comprehensive operational resilience.

Earlier investigations frequently evaluated genetic algorithms, particle swarm optimization, ant colony optimization, reinforcement learning, or evolutionary computation independently. Results presented here complement those perspectives by integrating multiple computational intelligence approaches into a unified optimization framework capable of coordinating renewable forecasting, battery storage scheduling, distributed generation, adaptive demand response, and real-time power system control. Such integration provides a more comprehensive understanding of intelligent grid operation because operational resilience emerges through interactions among complementary optimization techniques rather than isolated computational methods.

Differences also emerge regarding the strategic role of computational convergence. Existing optimization literature often evaluates convergence primarily as a mathematical performance indicator associated with algorithm efficiency. Findings from this study indicate that faster computational convergence contributes directly to operational resilience because rapid optimization enables electricity networks to respond more effectively to renewable intermittency, demand fluctuations, equipment failures, and environmental uncertainty. Computational convergence therefore possesses practical engineering significance beyond algorithm evaluation.

Current renewable energy optimization research frequently emphasizes operational objectives such as economic dispatch, energy scheduling, or loss minimization without adequately explaining how intelligent optimization strengthens long-term system resilience. Findings demonstrate that distributed energy coordination moderates the relationship between computational intelligence and grid sustainability, suggesting that future optimization research should increasingly integrate distributed resource management with resilience-oriented smart grid architectures.

Observed findings indicate that renewable energy grids should be understood as adaptive cyber-physical systems requiring continuous computational learning rather than fixed operational infrastructures. Electricity distribution networks demonstrating stronger resilience consistently integrated intelligent optimization, distributed energy coordination, renewable forecasting, and adaptive operational control before measurable improvements in technical performance became evident. Sustainable power distribution therefore reflects computational adaptability as much as engineering infrastructure.

Computational intelligence similarly emerges as an operational decision-support ecosystem rather than a collection of optimization algorithms. Intelligent systems continuously learn from changing electricity demand, renewable generation variability, weather conditions, battery availability, and network operating states to generate increasingly effective operational decisions. Grid optimization consequently evolves through continuous adaptation instead of repetitive numerical computation.

Distributed energy resources represent another important indicator because renewable electricity systems integrating battery storage, distributed generation, demand response, and intelligent forecasting consistently demonstrated greater operational flexibility and resilience. Distributed coordination enables electricity networks to absorb renewable variability while maintaining power quality and operational stability. Intelligent integration therefore becomes fundamental to future renewable electricity systems.

Digital infrastructure further signals technological maturity because advanced monitoring platforms, smart meters, communication networks, forecasting systems, and real-time analytics substantially strengthen optimization quality. Intelligent electricity networks consequently depend upon seamless interaction among computational intelligence, communication technologies, and engineering decision-making rather than isolated technological innovation.

Scientific implications suggest that renewable energy optimization research should increasingly integrate computational intelligence, power system engineering, operations research, artificial intelligence, control engineering, cyber-physical systems, and sustainability science into interdisciplinary frameworks capable of explaining resilient electricity distribution. Broader theoretical integration therefore provides stronger explanatory capacity than optimization approaches emphasizing algorithm performance alone.

Engineering implications encourage electricity utilities to reposition computational intelligence as a strategic operational capability rather than merely a computational support tool. Hybrid optimization, adaptive forecasting, intelligent storage management, distributed generation coordination, and demand response optimization should therefore become integral components of modern renewable grid architecture. Strategic computational investment consequently strengthens both operational resilience and renewable energy utilization.

Practical implications extend to utility operators, transmission system operators, renewable energy developers, electricity market regulators, computational scientists, and smart grid planners responsible for future energy system development. Findings indicate that integrating computational intelligence with distributed energy coordination substantially improves electricity reliability, renewable integration, operational flexibility, and economic sustainability. Comprehensive intelligent optimization therefore supports long-term energy transition objectives while improving system performance (Bhagat et al., 2025; Yuvaraj et al., 2024).

Societal implications include stronger energy security, reduced greenhouse gas emissions, improved electricity reliability, greater renewable energy adoption, enhanced environmental sustainability, and accelerated achievement of global decarbonization goals. Intelligent renewable grid optimization therefore contributes simultaneously to technological innovation, environmental protection, economic efficiency, and sustainable energy development.

Superior optimization performance primarily resulted from the adaptive search capability of hybrid computational intelligence algorithms, which efficiently explored highly nonlinear and multidimensional optimization spaces while continuously balancing conflicting operational objectives. Renewable electricity networks consequently achieved better operational decisions because optimization algorithms dynamically responded to changing system conditions instead of relying upon predetermined operational rules.

Renewable forecasting further strengthened optimization effectiveness because computational intelligence continuously incorporated updated meteorological information, electricity demand projections, battery availability, and distributed generation performance into operational planning. Improved prediction accuracy reduced unnecessary reserve generation, minimized renewable curtailment, and enhanced operational efficiency across all benchmark systems. Forecast-driven optimization therefore substantially improved renewable electricity utilization.

Distributed energy coordination significantly reinforced operational resilience because intelligent optimization synchronized multiple energy resources through adaptive control mechanisms. Renewable generators, battery storage systems, flexible loads, electric vehicles, and demand response resources consequently operated cooperatively rather than independently, improving network flexibility while reducing operational instability. Coordinated energy management therefore strengthened overall system resilience.

Real-time computational capability similarly amplified optimization quality because intelligent algorithms continuously evaluated network conditions, detected operational deviations, and generated corrective actions with minimal computational delay. Electricity networks consequently maintained greater stability despite rapidly changing renewable generation and electricity demand. Computational responsiveness therefore became a fundamental determinant of resilient renewable grid operation (Tang et al., 2023; Zhou et al., 2025).

Future investigations should examine intelligent renewable grid optimization through longitudinal operational studies evaluating algorithm performance across extended periods of seasonal variability, renewable generation uncertainty, evolving electricity markets, and infrastructure modernization. Long-term evidence would clarify how computational intelligence adapts to continuous technological and environmental change while maintaining sustainable operational performance.

Comparative investigations involving national transmission systems, regional distribution networks, isolated microgrids, community energy systems, industrial renewable facilities, offshore renewable installations, and cross-border electricity markets deserve continued attention because operational characteristics differ substantially across energy infrastructures and regulatory environments. Comparative evidence would support development of scalable optimization frameworks applicable across diverse electricity systems.

Emerging technologies including quantum computing, federated learning, digital twins, explainable artificial intelligence, edge intelligence, blockchain-enabled energy transactions, autonomous energy management, and next-generation cyber-physical systems present valuable opportunities for strengthening renewable grid optimization. Future research should investigate how these technologies enhance computational efficiency while maintaining cybersecurity, operational transparency, regulatory compliance, and engineering reliability.

Interdisciplinary collaboration among electrical engineers, computational intelligence researchers, artificial intelligence specialists, energy economists, sustainability scientists, control engineers, policymakers, and utility practitioners will remain essential for advancing renewable energy optimization research. Continued integration of intelligent algorithms, adaptive control, distributed energy coordination, digital infrastructure, and sustainability science will contribute substantially to developing resilient electricity systems capable of supporting future low-carbon energy transitions under increasingly complex operational conditions.

CONCLUSION

Findings demonstrate that computational intelligence and hybrid heuristic algorithms substantially improve the resilience and sustainability of renewable energy grids by simultaneously optimizing renewable energy utilization, power loss reduction, voltage stability, frequency regulation, battery energy storage scheduling, and operational efficiency. Distinctive evidence from this study indicates that hybrid optimization approaches outperform conventional deterministic methods because they effectively integrate adaptive learning, distributed energy coordination, and real-time operational decision-making under uncertain renewable generation conditions. Computational convergence partially mediates the relationship between intelligent optimization and grid resilience, while renewable forecasting accuracy and distributed energy coordination further strengthen sustainable power distribution. These findings redefine renewable grid optimization as an adaptive cyber-physical decision architecture in which computational intelligence continuously coordinates generation, storage, demand response, and network operation to maintain reliable and environmentally sustainable electricity delivery.

Scientific contribution of this research extends both conceptually and methodologically. Conceptually, the study proposes an integrated optimization framework that combines computational intelligence, heuristic optimization, smart grid engineering, renewable energy systems, adaptive control, cyber-physical system theory, and sustainability science to explain how intelligent optimization enhances resilient electricity distribution. Methodologically, the mixed-methods sequential explanatory design combines large-scale simulation experiments, benchmark power system evaluation, structural equation modeling, mediation and moderation analyses, expert interviews, engineering case studies, and technical document analysis to capture both computational performance and practical implementation mechanisms. Integration of quantitative and qualitative evidence provides a comprehensive understanding of intelligent renewable grid management while offering an evidence-based framework for utility operators, system planners, and policymakers responsible for accelerating sustainable energy transitions.

Scope of this investigation remains limited to benchmark distribution networks and simulated renewable energy scenarios, which may not fully represent the operational complexity of large-scale interconnected transmission systems, cross-border electricity markets, or highly heterogeneous smart grid infrastructures. Variations in renewable resource availability, regulatory frameworks, communication architectures, cybersecurity requirements, market mechanisms, and regional operating conditions may influence the broader applicability of these findings. Future research should therefore undertake longitudinal field validation using operational smart grids while incorporating quantum optimization, federated learning, explainable artificial intelligence, digital twins, blockchain-enabled energy management, edge intelligence, vehicle-to-grid integration, and climate-resilient energy planning to examine how next-generation computational intelligence can further strengthen resilient, secure, and sustainable renewable electricity systems.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used BlackBox AI to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abu, S. M., Hannan, M. A., Rahman, S. A., Ker, P. J., & Long, C. Y. (2025). Optimization algorithms for hybrid energy storage systems based microgrid performance enhancement. Energy, 332, 137304. https://doi.org/https://doi.org/10.1016/j.energy.2025.137304

Afzal, A., Buradi, A., Jilte, R., Shaik, S., Kaladgi, A. R., Arıcı, M., Lee, C. T., & Nižetić, S. (2023). Optimizing the thermal performance of solar energy devices using meta-heuristic algorithms: A critical review. Renewable and Sustainable Energy Reviews, 173, 112903. https://doi.org/https://doi.org/10.1016/j.rser.2022.112903

Ahmad Iqbal, M., & I. Almaraj, I. (2025). Short-term scheduling optimization of battery electric buses in the context of sustainable energy resources under uncertainty. International Journal of Electrical Power & Energy Systems, 168, 110715. https://doi.org/https://doi.org/10.1016/j.ijepes.2025.110715

Al-Shalabi, M., Shehab, M., Alshammari, M. T., Alazmi, M., Alrawashdeh, R. O., Abualigah, L., & Mahdi, M. A. (2025). Optimal sizing of smart hybrid renewable energy system using Lotus Effect Optimization Algorithm. Energy Reports, 14, 1936–1948. https://doi.org/https://doi.org/10.1016/j.egyr.2025.08.007

aldhahri, E. A., Almazroi, A. A., & Ayub, N. (2024). Nature-inspired approaches for clean energy integration in smart grids. Alexandria Engineering Journal, 105, 640–654. https://doi.org/https://doi.org/10.1016/j.aej.2024.08.003

Araoye, T. O., Ashigwuike, E. C., Mbunwe, M. J., Bakinson, O. I., & Ozue, T. I. (2024). Techno-economic modeling and optimal sizing of autonomous hybrid microgrid renewable energy system for rural electrification sustainability using HOMER and grasshopper optimization algorithm. Renewable Energy, 229, 120712. https://doi.org/https://doi.org/10.1016/j.renene.2024.120712

Asghari, M., Afshari, H., Jaber, M. Y., & Searcy, C. (2025). Enhancing grid stability: A weather-adaptive robust optimization to mitigating renewables curtailment. Renewable and Sustainable Energy Reviews, 219, 115874. https://doi.org/https://doi.org/10.1016/j.rser.2025.115874

Assareh, E., Izadyar, N., Jamei, E., Monzavian, M. amin, Agarwal, S., & Agarwal, N. (2025). Optimizing solar-powered multi-generation systems for sustainable energy management in university buildings using Neural Networks and Genetic Algorithms. Journal of Building Engineering, 108, 112939. https://doi.org/https://doi.org/10.1016/j.jobe.2025.112939

Assareh, E., Izadyar, N., Tandis, E., Khiadani, M., shahavand, A., Agarwal, N., Gerami, A., Rezk, A., Kim, M., Kord, R., Pirhoushyaran, T., Hosseinzadeh, M., & Mobayen, S. (2025). Thermoeconomic optimization of climate-adaptive solar and wind multi-generation systems using artificial intelligence and thermal energy recovery. Engineering Applications of Artificial Intelligence, 162, 112481. https://doi.org/https://doi.org/10.1016/j.engappai.2025.112481

Babosalam, S., Kargar, S. M., Moazzami, M., & Zanjani, S. M. (2025). Occupancy-aware energy optimization in building-to-grid systems using deep neural networks and model predictive control. Journal of Building Engineering, 112, 113714. https://doi.org/https://doi.org/10.1016/j.jobe.2025.113714

Bhagat, R. M., Jasutkar, D. B., Ranit, A. B., Vairagade, V. S., Yelamasetti, B., Shelare, S. D., Sharma, S., Mahapatro, A., Bupesh Raja, V. K., Naveed, Q. N., Kraiem, N., Islam, S., & Lozanovic, J. (2025). Machine learning and optimization in hybrid energy storage systems: Integrating MPC, PSO, MILP, and ANN for grid stability and efficiency. International Journal of Electrical Power & Energy Systems, 170, 110904. https://doi.org/https://doi.org/10.1016/j.ijepes.2025.110904

Bilal, M., Bokoro, P. N., & Sharma, G. (2025). Hybrid optimization for sustainable design and sizing of standalone microgrids integrating renewable energy, diesel generators, and battery storage with environmental considerations. Results in Engineering, 25, 103764. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103764

Bilal, M., Oladigbolu, J. O., Mujeeb, A., & Al-Turki, Y. A. (2024). Cost-effective optimization of on-grid electric vehicle charging systems with integrated renewable energy and energy storage: An economic and reliability analysis. Journal of Energy Storage, 100, 113170. https://doi.org/https://doi.org/10.1016/j.est.2024.113170

Chen, J., Aurangzeb, M., Iqbal, S., Shafiullah, M., & Harrison, A. (2025). Advancing EV fast charging: Addressing power mismatches through P2P optimization and grid-EV impact analysis using dragonfly algorithm and reinforcement learning. Applied Energy, 394, 126157. https://doi.org/https://doi.org/10.1016/j.apenergy.2025.126157

Dan, Z., Zhou, B., & Zhou, Y. (2025). Optimal infrastructures and integrative energy networks for sustainable and energy-resilient city renaissance. Applied Energy, 387, 125612. https://doi.org/https://doi.org/10.1016/j.apenergy.2025.125612

Gabber, H. A., & Hemied, O. S. (2025). MG-OPT: intelligent multi-objective Pareto-based optimization framework and transactive energy for Hybrid Renewable Energy Systems with hydrogen integration. Energy Conversion and Management, 341, 120042. https://doi.org/https://doi.org/10.1016/j.enconman.2025.120042

Gao, Q., Shen, L., Shi, J., Gu, X., Gu, S., Ge, Y., Xie, Y., Zhu, X., Zang, B., Zhang, M., Nazir, M. S., & Ji, J. (2025). Transformer-Enhanced Intelligent Microgrid Self-Healing: Integrating Large Language Models and Adaptive Optimization for Real-Time Fault Detection and Recovery. Energy Engineering, 122(7), 2767–2800. https://doi.org/https://doi.org/10.32604/ee.2025.065600

Gbadega, P. A., Sun, Y., & Balogun, O. A. (2025a). A Unified Optimization Framework for Cost-Effective and Voltage-Stable Operation of Renewable Energy-Based Microgrids Using Mixed-Integer Nonlinear Programming. E-Prime - Advances in Electrical Engineering, Electronics and Energy, 12, 101010. https://doi.org/https://doi.org/10.1016/j.prime.2025.101010

Gbadega, P. A., Sun, Y., & Balogun, O. A. (2025b). Optimized energy management in Grid-Connected microgrids leveraging K-means clustering algorithm and Artificial Neural network models. Energy Conversion and Management, 336, 119868. https://doi.org/https://doi.org/10.1016/j.enconman.2025.119868

Hussain, S., Imran Azim, M., Lai, C., & Eicker, U. (2025). Smart home integration and distribution network optimization through transactive energy framework – a review. Applied Energy, 395, 126193. https://doi.org/https://doi.org/10.1016/j.apenergy.2025.126193

Kashki, A., Azarfar, A., Samiei Moghaddam, M., & Davarzani, R. (2024). Optimal charging of electric vehicles in smart stations and its effects on the distribution network using meerkat optimization algorithm. Energy Reports, 12, 1936–1946. https://doi.org/https://doi.org/10.1016/j.egyr.2024.08.005

Kumar, R., Bera, C., & Kumar, A. (2025). Experimental verification and analysis of a novel HMRFO-AAA heuristic method utilizing Z-source DC/DC converter using HIL for DC-microgrid connected intelligent PV–hybrid energy storage systems. Journal of Energy Storage, 135, 118270. https://doi.org/https://doi.org/10.1016/j.est.2025.118270

Mbasso, W. F., Harrison, A., Jangir, P., Dagal, I., Khishe, M., Smerat, A., Chebaane, S., & Saidani, T. (2025). Reliability-conscious power flow optimization in hybrid renewable microgrids: a case study in Sub-Saharan Africa using Gauss-Seidel and metaheuristic techniques. International Journal of Electrical Power & Energy Systems, 173, 111350. https://doi.org/https://doi.org/10.1016/j.ijepes.2025.111350

Mohammed, H. I., Rashid, F. L., Togun, H., Agyekum, E. B., Ameen, A., Hammoodi, K. A., Parveen, R., Kadhim, S. A., & Abbas, W. N. (2025). The role of nanotechnology and artificial intelligence in optimizing thermal energy systems. Applied Energy, 400, 126576. https://doi.org/https://doi.org/10.1016/j.apenergy.2025.126576

Naderi, E. (2025). Securing the future: Integrating quantum computing and digital twin technologies into modern power & transportation systems for resilient smart cities against false data injection cyberattacks. International Journal of Critical Infrastructure Protection, 51, 100807. https://doi.org/https://doi.org/10.1016/j.ijcip.2025.100807

Ouyang, C., Khoshgoftar Manesh, M. H., Mousavi Rabeti, S. A., Ameryan, A., Sayyar, R., Jin, L., Zhou, Y., & Yunxia, G. (2025). AI-optimized solar-wind polygeneration for sustainable power and hydrogen: A pathway to a cleaner future. Energy, 341, 139458. https://doi.org/https://doi.org/10.1016/j.energy.2025.139458

Pramila, V., Kannadasan, R., J, B., Rameshkumar, T., Alsharif, M. H., & Kim, M.-K. (2024). Smart grid management: Integrating hybrid intelligent algorithms for microgrid energy optimization. Energy Reports, 12, 2997–3019. https://doi.org/https://doi.org/10.1016/j.egyr.2024.08.053

Tang, L., Kong, T., & Innab, N. (2023). Eagle arithmetic optimization algorithm for renewable energy-based load frequency stabilization of power systems. Sustainable Computing: Informatics and Systems, 40, 100925. https://doi.org/https://doi.org/10.1016/j.suscom.2023.100925

Tiam Kapen, P. (2025). Sustainable cities and societies through innovative optimization of off-grid biomass/photovoltaic/battery and wind/photovoltaic/battery hybrid systems under diverse climatic conditions. Results in Engineering, 28, 108091. https://doi.org/https://doi.org/10.1016/j.rineng.2025.108091

Varghese, T., Arun, N. K., & Pathirikkat, G. (2025). Congestion management in power grids using multi-agent systems and particle swarm optimization. Franklin Open, 12, 100303. https://doi.org/https://doi.org/10.1016/j.fraope.2025.100303

Wang, L., & Sun, N. (2025). Next-Generation energy Management: Particle Density algorithm for residential microgrid optimization. Egyptian Informatics Journal, 29, 100611. https://doi.org/https://doi.org/10.1016/j.eij.2025.100611

Yuvaraj, T., Krishnamoorthy, R., Arun, S., Thanikanti, S. B., & Nwulu, N. (2024). Optimizing virtual power plant allocation for enhanced resilience in smart microgrids under severe fault conditions using the hunting prey optimization algorithm. Energy Reports, 11, 6094–6108. https://doi.org/https://doi.org/10.1016/j.egyr.2024.05.043

Zereg, H., & Bouzgou, H. (2025). Forecast-integrated techno-economic optimization of off-grid hybrid renewable system in hyper-arid regions: Application to Tamanrasset, Algeria. Energy, 334, 137468. https://doi.org/https://doi.org/10.1016/j.energy.2025.137468

Zhou, Y., Ning, Z., Huang, K., Guo, S., Xu, C.-Y., & Chang, F.-J. (2025). Sustainable energy integration: Enhancing the complementary operation of pumped-storage power and hydropower systems. Renewable and Sustainable Energy Reviews, 210, 115175. https://doi.org/https://doi.org/10.1016/j.rser.2024.115175