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Innovations in integrated energy systems and smart grid optimization for sustainable development: a review

Abstract

The evolving landscape of power and energy systems demands innovative approaches to achieve sustainability, efficiency, and reliability. This review synthesizes recent research advances in integrated energy-water nexus optimization, energy sharing among smart buildings, non-intrusive load disaggregation using neural networks, and low-carbon dispatch strategies. Emphasizing quantum-classical robust optimization, mobile energy storage, attention-based load analysis, and adaptive dispatching, the article highlights the significant progress toward smarter, cleaner, and more resilient energy infrastructures. These methodologies enable better resource utilization, demand management, and decarbonization efforts, aligning with global sustainability goals.

Keywords: Energy-water nexus, smart buildings, load disaggregation, robust optimization, energy sharing, low-carbon dispatch, sustainable energy systems

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Introduction

The pursuit of sustainable energy development requires integrated approaches that consider multiple resources, energy, water, and demand-side flexibility, and advanced computational techniques.[1,2] Rapid technological advancements and the integration of renewable resources have necessitated innovative optimization strategies to manage complexity, uncertainty, and resource constraints effectively.[3,4] This review explores recent breakthroughs in several key areas: The optimization of the energy-water nexus in rural microgrids, Strategies for sharing energy across interconnected smart buildings, non-intrusive load disaggregation using artificial intelligence, Low-carbon optimal dispatching for energy-intensive industrial parks.[5] For example, detailing a scenario where a cluster of buildings uses predictive algorithms to optimize EV charging schedules based on real-time energy prices and grid load could provide a more concrete illustration. By understanding these developments, stakeholders can better design resilient, efficient, and environmentally friendly energy systems that support future sustainability targets.

Energy-water nexus optimization using quantum-classical techniques

Water and energy systems are deeply interconnected; the consumption of water for cooling, hydroelectric generation, and industrial processes impacts energy production, while energy is essential for water treatment and distribution.[6,7] Optimizing this nexus is complex due to the multifaceted interactions and uncertainties involved. Recent research introduces quantum-classical robust optimization methods to address the complexity and uncertainty inherent in rural microgrids, which often incorporate renewable sources, water pumping, and desalination units. Quantum computing techniques offer enhanced computational capabilities, enabling more accurate and faster solutions over classical methods.[8] The proposed approach integrates these quantum algorithms with traditional optimization to achieve a balanced trade-off between sustainability and operational cost.[9] The model considers water and energy resource constraints, variability in renewable generation, and climate factors, providing a resilient plan for microgrid operation that maximizes resource efficiency (Figure 1).

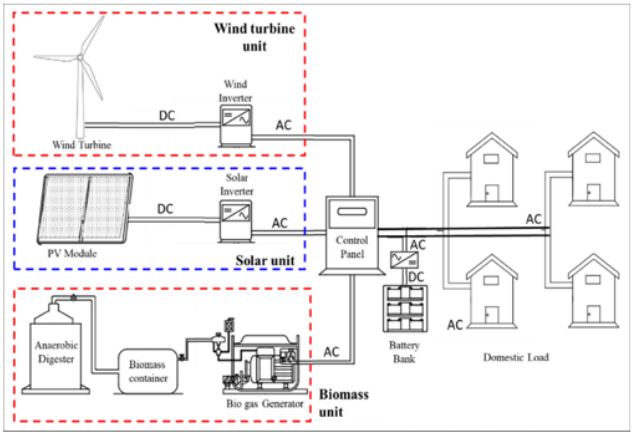

Figure 1 Schematic of integrated energy-water microgrid showing renewable sources, water treatment units, and energy storage.

Energy sharing among smart building clusters with mobile storage

Building clusters in urban areas can collaboratively share energy resources, such as surplus solar generation or stored energy, thereby reducing dependence on the grid and lowering carbon emissions. The optimization of energy sharing must consider the unique characteristics of mobile energy storage devices, primarily electric vehicles (EVs).[10,11] An innovative strategy involves modeling EVs as mobile energy storage units capable of both supplying and absorbing energy, depending on demand and grid conditions. The energy sharing optimization problem considers factors like the mobility patterns of EVs, varying load demands, and incentives for participation. By employing advanced algorithms that coordinate energy exchanges within building clusters and optimize EV charging/discharging, the system can significantly improve peak shaving, reduce energy costs, and enhance flexibility (Table 1).[12]

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Table 1 Comparative analysis of static vs. mobile energy storage efficiency in smart building clusters

Type	Energy Density (Wh/kg)	Energy Efficiency (%)	Power Density (W/Kg)	Life Time (Cycles)	Self Discharge (%/Month)	Environmental Effect
Battery	25 - 250	60 - 90	100 - 3000	150 - 3000	3 - 30	Toxic
Ultra Capacitor	<50	95	4000	10 k - 100 k	High	Benign
Flywheel	100 - 130	95	1000	>125,000	High	Benign
SMES	30 - 80	95	Very High	-	Negligible	Benign
CAES	10 - 30	50	Fair	40 Years	Negligible	Benign
PHS	0.3	65 - 80	-	75 Years	Negligible	Benign

Non-intrusive load disaggregation based on attention neural networks

Effective demand-side management requires detailed knowledge of individual appliance consumption within a household or industrial facility.[13] Traditional load monitoring involves intrusive submeters, which are costly and invasive. Recent advances leverage deep learning, especially attention-based neural networks, to perform non-intrusive load disaggregation (NILM). This technique dissects aggregate power consumption data to identify and estimate the usage patterns of individual appliances without additional sensors.[14,15] The proposed attention neural network models assign dynamic weights to features of the measured data, capturing temporal dependencies and contextual information more accurately.[16,17] This leads to improved disaggregation accuracy, facilitating smarter demand response, energy efficiency programs, and fault detection.

Low carbon optimization dispatch for energy-intensive industrial parks

Industrial parks contribute significantly to carbon emissions due to their high energy consumption. Adopting low-carbon dispatch strategies involves optimizing at the operational level to minimize greenhouse gas emissions while maintaining process efficiency and output. An adaptive step dispatching approach considers dynamic factors such as fluctuating renewable generation, market prices, and carbon credits. The method adjusts generation and consumption schedules in real-time, prioritizing renewable sources and low-emission technologies.[18,19] This strategy aligns with avatar reducing industrial carbon footprints while ensuring economic viability. The approach employs real-time data analytics and adaptive algorithms to respond effectively to operational uncertainties and market dynamics, fostering a sustainable industrial environment (Figure 2 & 3).

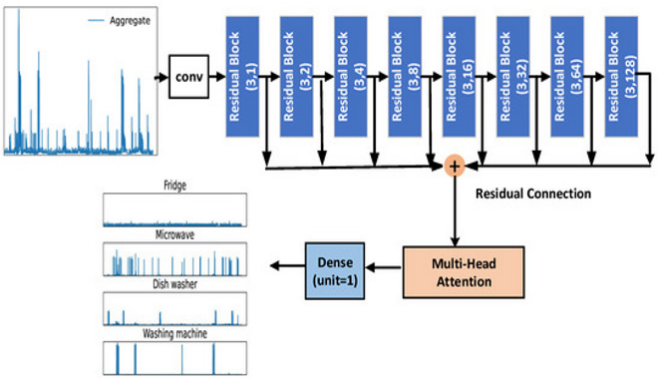

Figure 2 Illustration of attention neural network architecture for load disaggregation.

Practical implications and future directions

The integration of quantum computing for resource management promises significant computational efficiency for complex systems, especially in the energy-water nexus. Smart building clustering and energy sharing frameworks offer scalable solutions for urban resilience and demand flexibility. Non-intrusive load disaggregation through attention neural networks provides a pathway toward smarter demand response, fault detection, and energy auditing without invasive equipment. Lastly, adaptive low-carbon dispatching embodies the transition toward cleaner industrial operations, aligning technological innovation with environmental policies. Future research should focus on synergizing these techniques into holistic systems, utilizing machine learning, blockchain, and IoT technologies to enhance transparency, security, and scalability. Developing standardized frameworks and interoperability protocols will accelerate adoption across different sectors.

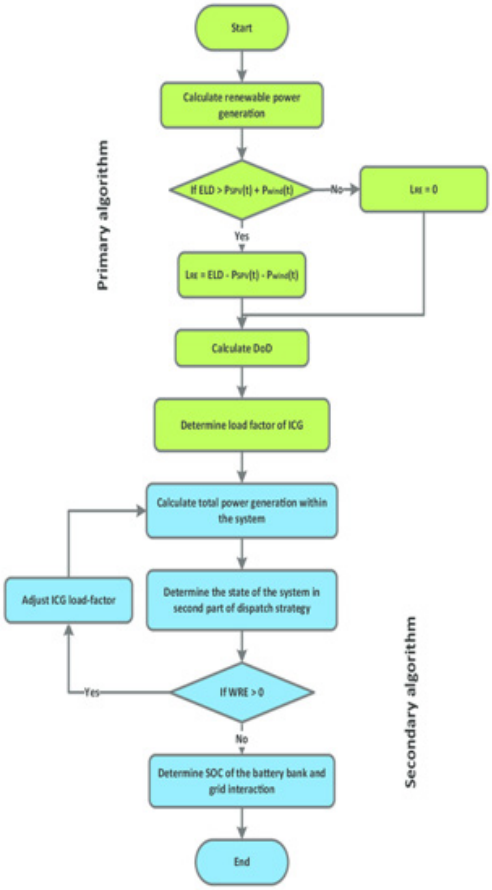

Figure 3 Flowchart of the adaptive step dispatching process with real-time data integration.

Conclusion

The reviewed studies underscore the critical role of cutting-edge technological solutions in constructing sustainable, efficient, and resilient energy systems. Quantum-classical optimization advances enable more effective management of critical resources such as water and energy. Collaborative energy sharing and AI-driven load disaggregation support smarter demand-side management, highlighting the importance of integrating data-driven techniques. Moreover, adaptive dispatching strategies exemplify how operational flexibility can significantly reduce carbon emissions in high-energy-use industrial sectors. As these approaches mature and integrate, they will form the backbone of future energy infrastructures aligned with global sustainability goals.

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