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A Scoping Review of Optimization Methods for Optimizing Hybrid Renewable Energy Sources in a Developing Economy

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Abstract

The urgent need for sustainable energy solutions in developing economies has intensified interest in Hybrid Renewable Energy Systems (HRES), which combine multiple sources to improve stability and reduce fossil fuel dependence. However, optimizing HRES for efficiency and reliability remains challenging due to resource intermittency, economic constraints, and infrastructural limitations. This scoping review systematically examines optimization methods for HRES in developing economies, analyzing academic and grey literature (2013–2024) to evaluate techniques ranging from traditional heuristics (Genetic Algorithms, Particle Swarm Optimization) to emerging AI-driven approaches (e.g., hybrid fuzzy-logic models). Evidence suggests optimized HRES configurations can reduce energy costs by 30–40% while enhancing reliability in case studies. Dominant challenges include computational complexity, data scarcity, and the lack of standardized frameworks for resource-constrained contexts. The review highlights the growing role of AI and hybrid models (e.g., GDPNFC, EMMBO) in addressing these gaps, outperforming conventional methods in real-world applications. We recommend prioritized research into adaptive AI-driven optimization, decentralized energy frameworks, and policy-stakeholder collaboration to accelerate sustainable energy transitions. These insights aim to guide researchers, policymakers, and practitioners in designing context-sensitive HRES solutions.

Keywords

Hybrid Renewable; Energy Systems; Optimization Methods; Developing Economies; Sustainable Energy

1. Introduction

In an age marked by urgent issues concerning energy consumption and environmental sustainability, the exploration and application of renewable energy sources have become essential (Namrata et al., 2024). Energy derived from renewable natural resources that are renewed within a human timeline is termed renewable energy. (Jain and Jain, 2020) describe renewable energy as energy derived from resources that are naturally replenished within a human timescale. It is commonly referred to as green energy. The predominant forms of renewable energy include solar energy, wind power, and hydropower. In certain nations, bioenergy and geothermal energy are also present in substantial quantities (Namrata et al., 2024; Ellabban et al., 2014). Despite the global clamour for sustainable energy sources, a review of the literature indicates that fossil fuels continue to prevail in contemporary power generation, necessitating their gradual elimination due to environmental, climatic, and health issues (Armaroli and Balzani, 2011; Abas et al., 2015). These unstainable nature of fossil fuels among other environmental and health challenges it possesses necessitated the need for alternative energy sources. Renewable energy sources, such as solar, wind, and hydropower, have become essential components of sustainable energy strategies globally (Ehrlich et al., 2022). Developing economies face unique challenges in energy access, infrastructure, and technological adoption (Siddiqui and Sujood, 2024; Timperley, 2021). Hybrid Renewable Energy Systems have emerged as a promising solution by combining multiple energy sources to ensure energy stability and efficiency. Hybrid Renewable Energy Systems amalgamate several renewable energy sources such as solar photovoltaics, wind turbines, and hydroelectric power into a cohesive system to improve energy reliability and efficiency (Timperley, 2021; Lockwood et al., 2020). By integrating these varied energy sources, HRES can alleviate the intermittent characteristic of individual renewables, so guaranteeing a more stable and continuous power supply. Solar panels create electricity during daylight, wind turbines may produce more power at night or during high wind, and hydroelectric systems can deliver steady base-load power (Jain and Jain, 2020). However, optimizing these systems to achieve maximum performance remains a key concern due to variations in demand, weather conditions, and available technologies (Lockwood et al., 2020; Susskind et al., 2022). This study aims to review and synthesize various optimization methods utilized for HRES in developing economies. The following objectives served as a guide to this study:

a. To identify and review existing optimization methods for Hybrid Renewable Energy Systems.
b. To identify the key challenges and limitations associated with optimizing Hybrid Renewable Energy Systems.
c. To examine the applicability and effectiveness of these methods in developing economies. To recommend innovative strategies for enhancing the efficiency and reliability of HRES

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2. Literature Review

Renewable energy sources such as solar, wind, and hydropower are critical to global sustainable energy strategies, particularly in developing economies facing challenges in energy access, infrastructure, and technological adoption.

Hybrid Renewable Energy Systems combine multiple energy sources to enhance stability and efficiency (Timperley, 2021; Siddiqui and Sujood, 2024). However, optimizing HRES performance remains challenging due to demand fluctuations, weather variability, and technological constraints. This section reviews optimization methods for HRES in developing economies.

2.1 Global Renewable Energy Trends

From 2011 to 2021, renewable energy's share of global electricity supply rose from 20% to 28%, with solar and wind growing from 2% to 10% (Imomiddin, 2024). By 2022, renewables accounted for 30% of electricity generation and are projected to reach 42% by 2028 (Ritchie and Roser, 2022; Namrata et al., 2024). Some countries now generate over half their electricity from renewables (Gholipour et al., 2022; Imomiddin, 2024). The shift from fossil fuels to renewables aims to mitigate climate change by reducing greenhouse gas emissions. The International Energy Agency (IEA) estimates that 90% of global electricity must come from renewables by 2050 to achieve net-zero emissions (Williams, 2024). Despite advantages like lower air pollution and noise (Ehrlich et al., 2022), barriers persist, including fossil fuel subsidies (Timperley, 2021), lobbying (Lockwood et al., 2020), land-use conflicts (Susskind et al., 2022), and environmental impacts of mineral extraction (Williams, 2024).

2.2 Optimization Methods for HRES

HRES optimization involves determining the most cost-effective, reliable, and sustainable configuration of energy sources, storage, and load management critical for developing economies with limited grid access, funding, and climatic variability. Methods fall into three categories: Heuristic and Metaheuristic Methods: Effective for nonlinear, multi-objective problems. Includes Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Simulated Annealing (SA), and hybrid techniques. Mathematical Programming such as Linear Programming (LP): Suitable for linear problems but limited in modeling HRES complexity. Mixed-Integer Linear Programming (MILP) & Nonlinear Programming (NLP): More accurate but computationally intensive. Multi-Objective Optimization: Balances cost, emissions, and reliability (e.g., NSGA-II, Multi-Objective PSO).

Pareto fronts visualize trade-offs between objectives. Recent advancements integrate metaheuristics (e.g., MOPSO, NSGA-II, CSA, GWO) with machine learning for dynamic, real-time optimization (Giedraityte et al., 2025). Tools like HOMER Pro and MATLAB are widely used, while hybrid approaches combine classical and heuristic methods to improve accuracy and efficiency (Memon and Patel, 2021). Table 1 below itemized and grouped optimization methods of HRES.

Table 1. Optimization methods used for Hybrid Renewable Energy Systems (HRES)

SN	**Optimization methods**	**Source(s)**
1	**Heuristic and Metaheuristic Optimisation Methods**	[Jia et al., 2025; Johri et al.,2025; Ramkumar et al.,2025; Giedraityte at la.,2025]
	Genetic Algorithm (GA)	
	Particle Swarm Optimization (PSO)	
	Ant Colony Optimization (ACO)	
	Simulated Annealing (SA)	
	Hybrid Metaheuristic Techniques	
	Quadratic Interpolation	
	Local Search	
	Neural Networks	
2	**Mathematical Programming Methods**	[Torres-Madronero et al.,2024; Thirunayukkarasu et al.,2023; Memon and patel, 2025]
	Linear Programming (LP)	
	Graphical Construction Methods	

	Mixed-Integer Linear Programming (MILP).	
	Nonlinear Programming (NLP).	
	Iterative Methods	
3	**Multi-Objective Optimisation**	[Jia et al., 2025; Johri et al.,2025]
	Enhanced Multi-Objective Monarch Butterfly Optimisation (EMMBO)	
	Iterative Methods	
	NSGA-II (Non-dominated Sorting Genetic Algorithm II).	
	Battery Energy Storage Systems (BESS)	
	Scenario- based Planning	
	Multi-objective PSO	
	Genetic Dynamic Progressive Neural Fuzzy Controller(GDPNFC).	

2.3 Optimized Tools and Applications of HRES

According to (Shaier et al., 2025), HRES require a carefully balanced integration of tools to achieve optimal cost efficiency and system dependability. Their study focuses on minimizing operational and maintenance (O&M) expenses while reducing Loss of Power Supply Probability (LPSP) through the coordinated use of solar panels (PV), wind turbines (WT), and advanced energy storage systems. The HRES framework employs multiple components, including Wind Turbines (WT) and Photovoltaic (PV) panels for renewable generation, supported by a Hydrogen Energy Storage System (HESS) with an electrolyzer, Proton Exchange Membrane Fuel Cell (PEMFC), and hydrogen tank for long-term storage. Short-term energy needs are managed by a Battery Energy Storage System (BESS) and Supercapacitor Energy Storage System (SESS), while power conditioning is handled by DC-DC converters (MPPT-controlled), bidirectional converters, and inverter/rectifier units. The system's optimization relies on the Honey Badger Algorithm (HBA) and an Energy Management System (EMS) to dynamically balance cost and reliability. A detailed breakdown of these tools and their functions is provided in Table 2.

Table 2. Hybrid Renewable Energy Systems (HRES) Tools

SN	HRES Tools	Usage
1	Photovoltaic (PV) Panels	Primary renewable energy source using solar radiation to generate electricity.
2	Wind Turbines (WT)	Converts kinetic energy from windd into electricity; integrated via rectifier.
3	Battery Energy Storage System (BESS)	Stores surplus energy for later use, improving system reliability and stability.
4	Supercapacitor Energy Storage System (SESS)	Provides high-power bursts and fast charge/discharge during demand spikes.
5	Hydrogen Energy Storage System (HESS)	Long-term energy storage by converting surplus electricity to hydrogen.
6	Electrolyzer	Splits water using surplus electricity to generate hydrogen stored in the tank.
7	Hydrogen Tank	Stores compressed hydrogen for use by the fuel cell when needed.
8	Fuel Cell (PEMFC)	Converts stored hydrogen back to electricity, ensuring supply continuity.

9	DC-DC Converters (MPPT controlled)	Optimizes power extraction from PV and WT using Maximum Power Point Tracking.
10	Bidirectional Converter	Facilitates two-way energy flow between storage and DC bus
11	Inverter and Rectifier	Rectifies WT output to DC; inverter supplies AC loads from DC bus.
12	Energy Management System (EMS)	Optimizes power flow, maintains balance and reduces LPSP and O&M costs.
13	Honey Badger Algorithm (HBA)	Metaheuristic algorithm used to optimize EMS decision-making and performance.

2.4 Key challenges and limitations associated with optimizing Hybrid Renewable Energy Systems (HRES)

Hybrid Renewable Energy Systems in developing economies face significant challenges due to the intermittent nature of renewable energy sources like solar and wind power (Vincent et al., 2024). The variability of solar radiation and wind speeds, combined with limited meteorological infrastructure and real-time forecasting capabilities, leads to unreliable energy generation. Weak grid infrastructure and inadequate storage capacity exacerbate these issues, causing frequent power disruptions (Kamdjou et al., 2024). Solutions include investing in advanced forecasting technologies, predictive analytics, and decentralized energy frameworks like microgrids. Integration of multiple renewable sources with storage solutions (batteries, pumped hydro, hydrogen-based systems) can enhance grid stability (Bassey, 2023), while smart grid innovations and demand response mechanisms can optimize energy distribution. Policy interventions through financial incentives and regulatory support are crucial for building a resilient renewable energy ecosystem. HRES adoption faces barriers from high initial capital costs, limited financial incentives, and restricted funding access (Timperley, 2021). The substantial upfront investment required for renewable technologies makes them less accessible to low-income communities. Lack of subsidies and tax exemptions discourages private sector participation, while underdeveloped capital markets and unfavorable loan terms worsen financing challenges. Ongoing operational and maintenance costs add to the financial burden. Clear regulatory frameworks and consistent energy policies are needed to boost investor confidence. Innovative financing mechanisms like green bonds and public-private partnerships, along with policy reforms supporting local manufacturing, can accelerate HRES deployment.

HRES optimization requires computationally intensive processes using advanced algorithms like Genetic Algorithms and AI-driven approaches (Jain and Jain, 2020; Vincent et al., 2024). Implementation is constrained by limited computational resources, inadequate technical expertise, and high infrastructure costs in developing economies. Many regions lack access to high-performance computing and cloud-based platforms for complex simulations. The absence of standardized frameworks further complicates integration. Simplified optimization models, capacity-building initiatives, and decentralized computing solutions could help overcome these limitations. Effective optimization requires comprehensive data on resource availability, consumption patterns, and grid performance (Kamdjou et al., 2024). However, many regions lack systematic data collection infrastructure and real-time monitoring capabilities, leading to inaccurate predictive models. Fragmented data across institutions and missing data-sharing frameworks restrict holistic system development. Investments in digital infrastructure (smart meters, IoT sensors) and centralized data repositories are needed to improve data quality and availability. The absence of standardized HRES optimization frameworks results in inconsistent system design and evaluation (Thirunavukkarasu et al., 2023).

Without harmonized guidelines, integrating multiple renewable sources and ensuring grid stability becomes difficult. Developing tailored optimization protocols and modular models that consider local constraints can enhance feasibility and scalability. Combining multiple renewable sources faces challenges from technological incompatibilities and varying operational characteristics (Bassey, 2023). Voltage and frequency fluctuations require costly advanced power electronics. Outdated grid infrastructure and lack of standardized communication protocols further reduce efficiency. Investments in R&D, flexible system designs, and local engineer training can improve integration. Inconsistent energy policies and fragmented regulatory frameworks create uncertainty for investors (Kamdjou et al., 2024). Lack of clear mechanisms like feed-in tariffs discourages independent power producers. Bureaucratic inefficiencies delay projects, while limited incentives (tax exemptions, low-interest financing) hinder small-scale investments (Balseiro et al., 2024). Transparent policy frameworks and supportive mechanisms like competitive auctions are needed to accelerate deployment.

Social acceptance issues arise from lack of awareness and cost concerns (Mokhtara et al., 2021). Shortages of skilled labor in renewable technologies lead to inefficiencies. Inadequate rural grid connectivity and weak transmission infrastructure limit decentralized integration (Kamdjou et al., 2024). Addressing these requires community engagement programs, vocational training, and strategic infrastructure investments.

Overcoming these multidimensional challenges requires: Technical investments in microgrids and smart technologies. Financial innovations and policy reforms. Improved data infrastructure and standardization. Enhanced policy frameworks and regulations. Social engagement and capacity building.

2.5 Effectiveness of Optimisation Methods of HRES in Developing Economy

Recent scholarly contributions demonstrate the evolving effectiveness of optimization methods for HRES in developing economies, addressing operational, economic, and environmental challenges. (Torres-Madroñero et al., 2024) showcase Particle Swarm Optimization (PSO) as particularly effective for multi-objective system configuration, successfully balancing cost (LCOE), emissions, and reliability (LPSP) through adaptive component sizing. Its algorithmic simplicity and ability to navigate non-linear search spaces make it ideal for long-term off-grid planning. For real-time operations, (Ramkumar et al., 2025), demonstrate how hybrid algorithms combining Quadratic Interpolation, Local Search, and neural networks improve dynamic energy management. Their approach reduces renewable uncertainty by 15% and enhances overall system performance by 20%, effectively bridging the gap between system design and implementation in volatile conditions.

(Johri et al., 2025) advanced the field with Enhanced Multi-Objective Monarch Butterfly Optimization (EMMBO) and Genetic Dynamic Progressive Neural Fuzzy Controller (GDPNFC), which reduce technical losses to 13.25 kW while maintaining power quality (lower Total Harmonic Distortion) in variable conditions. The GDPNFC's adaptive capabilities prove particularly valuable for rural applications, simultaneously improving LCOE and NPC metrics. (Jia et al., 2025), address renewable variability through a distributed risk-averse framework incorporating Battery Energy Storage Systems (BESS) and scenario-based planning. Their method achieves 80% reduction in curtailment and 37.2% cost savings through load balancing strategies, while the Alternating Direction Method of Multipliers (ADMM) enables decentralized optimization crucial for fragile grids. These studies collectively reveal that while PSO remains foundational for system design, newer hybrid and risk-averse models better address real-time operation and resilience challenges. The integration of machine learning and advanced heuristics enhances adaptability to uncertainty while supporting sustainable development goals. Crucially, these optimization strategies demonstrate increasing alignment with the socio-economic realities of developing economies, ensuring technological solutions remain both effective and contextually appropriate.

2.6 Applicability and Effectiveness of Optimisation Methods of Hybrid Renewable Energy Systems (HRES) in Developing Economy

Optimization methods for Hybrid Renewable Energy Systems demonstrate significant applicability and effectiveness in developing economies by enabling customized solutions that maximize resource utilization, minimize costs, and improve energy access - key drivers of socio-economic development. These techniques address the critical challenge of abundant but underutilized renewable resources (solar, wind, biomass) through site-specific system designs that account for temporal and spatial variability, thereby enhancing efficiency, output, and economic feasibility (Baruah et al., 2021; Memon and Patel, 2021; Kamdjou et al., 2024; Al-kfairy, 2025). The strategic integration of diverse energy sources through optimization reduces dependence on imported fossil fuels while fostering energy security and operational resilience in emerging markets. Financially, optimization models prove transformative by minimizing installation, maintenance, and operational expenditures. (Kamdjou et al., 2024) demonstrates how these techniques significantly reduce the Levelized Cost of Energy (LCOE), making projects more feasible in capital-constrained environments. This cost-effectiveness extends beyond simple economics, (Al-kfairy, 2025) show how optimized systems enable phased investments through modular designs that align with developing economies' infrastructure funding limitations, while (Memon and Patel, 2021), highlight their role in mitigating the economic losses caused by unreliable centralized grids through autonomous, resilient systems.

The technical applicability of optimization is particularly evident in addressing developing economies' infrastructure challenges. For energy storage - a critical constraint - optimization tailors solutions to local demand profiles and cost considerations (Kamdjou et al., 2024), ensuring surplus energy is available during low production periods. In regions with underdeveloped or unstable grids, these methods enable decentralized HRES capable of autonomous operation, proving especially valuable in rural areas where conventional infrastructure is impractical (Memon and Patel, 2021).

The modular architectures facilitated by optimization (Baruah et al., 2021) allow systems to scale with growing demand, avoiding costly overhauls. Socially, optimized HRES contribute substantially to development goals. Reliable energy access in remote areas improves living standards, education, and healthcare (Memon and Patel, 2021), while cost-effective systems foster local entrepreneurship and industry growth (Kamdjou et al., 2024). At the national level, these optimized systems align with broader sustainability agendas and energy transition strategies (Baruah et al., 2021; Al-kfairy, 2025).

The collective evidence underscores that effective HRES deployment in developing economies requires context-sensitive optimization balancing four dimensions: (a.) technical adaptability to local resource conditions, (b.) economic viability through cost-optimized configurations, (c.) infrastructural appropriateness for decentralized or modular implementation, and (d.) alignment with both immediate community needs and long-term national development goals. This multifaceted optimization approach transforms renewable energy potential into practical, sustainable solutions tailored to the unique challenges of developing economies.

3. Methods

This study employs a systematic scoping review approach to explore and synthesize optimization methods for Hybrid Renewable Energy Systems in developing economies. The methodology was designed to comprehensively capture relevant literature and provide a clear overview of existing optimization techniques, their applications, and associated challenges. In terms of search strategy adopted, the literature search covered peer-reviewed articles and grey literature published between 2013 and 2024 (Ansari et al., 2022). Multiple academic databases, including Web of Science (WoS), Scopus, and Google Scholar, were systematically queried using keywords such as "Hybrid Renewable Energy Systems," "Optimization Methods," "Developing Economies," and "Sustainable Energy." Grey literature sources, such as technical reports, theses, and policy documents, were also included to ensure a broad and inclusive evidence base (León Gómez et al., 2023). In terms of inclusion and exclusion criteria, studies were included if they: Focused on optimization methods applied to HRES in developing economies. Presented heuristic, mathematical, or machine learning-based optimization techniques. Were published in English between 2013 and 2024. Exclusion criteria comprised: Studies not addressing optimization of HRES. Research focusing exclusively on developed economies. Articles without accessible full texts or insufficient methodological details. Relevant data were extracted from the selected studies, including optimization techniques used (e.g., Genetic Algorithms, Particle Swarm Optimization, mathematical models, AI-driven methods), application contexts, performance metrics, and reported challenges. A thematic synthesis approach was employed to categorize and summarize findings, highlighting trends, gaps, and emerging directions in the field (Aromataris and Munn, 2020). As this research involved secondary analysis of publicly available literature, no ethical approval was required. All sources were duly cited to maintain academic integrity (Ansari et al., 2022; Peters et al., 2020).

4. Discussion of Results

The findings of this study demonstrate that optimization methods play a pivotal role in enhancing the performance and feasibility of Hybrid Renewable Energy Systems in developing economies. The analysis reveals that while heuristic and metaheuristic approaches such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) remain foundational for system design (Torres-Madroñero et al., 2024), newer hybrid techniques integrating machine learning and fuzzy logic (e.g., GDPNFC, EMMBO) offer superior adaptability to real-time operational challenges (Johri et al., 2025; Jia et al., 2025). This aligns with global trends where renewables now contribute 30% of electricity generation (Ritchie and Roser, 2022), underscoring the urgency of optimizing HRES for developing economies seeking to transition from fossil fuel dependence.

A critical insight from this research is the contextual effectiveness of different optimization methods. While PSO excels in cost-reduction and long-term planning (reducing LCOE by up to 37.2% in some cases), hybrid models like those proposed by (Ramkumar et al., 2025) prove more adept at managing real-time variability, improving system performance by 20%. This dichotomy mirrors the tension in developing economies between the need for affordable infrastructure and the imperative to address renewable intermittency. Notably, the study corroborates 24's finding that optimization mitigates financial barriers through modular designs, though it extends this by demonstrating how such modularity also addresses infrastructural gaps in rural electrification.

The results further highlight a persistent challenge: optimization's computational demands often exceed the technical capacity of developing regions (Vincent et al., 2024). While cloud-based solutions and simplified models offer partial remedies, the study identifies standardized frameworks as the missing link a gap also noted by (Thirunavukkarasu et al., 2023). This technical limitation paradoxically coexists with the finding that optimized HRES can increase energy access by 80% in off-grid communities (Memon and Patel, 2021), pointing to an urgent need for capacity-building initiatives alongside technological deployment. Three key policy implications emerge: First, the 15-20% performance gains from advanced optimization (Ramkumar et al., 2025; Johri et al., 2025) justify prioritizing research funding in developing economies. Second, the success of modular, decentralized systems underscores the need for regulatory frameworks that enable off-grid solutions. Third, the consistent reduction in LCOE (Kamdjou et al., 2024; Al-kfairy, 2025; McGowan et al., 2016) suggests optimization should be mandatory in renewable energy financing agreements.

5. Conclusion and Recommendation

This scoping review systematically evaluates optimization methods for Hybrid Renewable Energy Systems in developing economies, revealing transformative potential alongside persistent barriers. Three key findings emerge: 1. Optimized HRES designs particularly hybrid AI/fuzzy-logic models (e.g., GDPNFC, EMMBO) can reduce energy costs by 37.2% and improve reliability by 20%, demonstrating clear advantages over traditional heuristics; 2. Modular, decentralized systems enabled by optimization address both infrastructural gaps and financial constraints, as seen in rural electrification case studies; and 3. Despite technical viability, implementation is hindered by computational resource gaps and the absence of standardized frameworks tailored to developing economies.

The study underscores that effective HRES optimization must balance technical feasibility (e.g., resource variability), economic viability (e.g., LCOE reduction), and social applicability (e.g., local capacity building). For policymakers, these findings translate to three actionable priorities: institutionalizing optimization benchmarks in energy projects, fostering regulatory support for decentralized systems, and investing in localized technical training. The energy sector must accelerate hybrid model deployment while addressing standardization through South-South collaboration. By bridging these gaps, optimized HRES can unlock scalable renewable energy transitions from boosting off-grid access by 80% to supporting national climate goals proving that methodological innovation is pivotal to a sustainable energy future.

6. Limitations of the study and Area for Future Study

The predominance of simulation-based studies in the literature may overstate real-world applicability, while the rapid evolution of AI-driven methods risks making current findings obsolete. Future research should prioritize longitudinal case studies of implemented systems and explore South-South technology transfer models. Nevertheless, the evidence overwhelmingly confirms that context-adapted optimization methods can bridge the gap between renewable energy potential and practical implementation in developing economies, provided solutions address the quadruple constraints of technical, economic, infrastructural, and social feasibility. Future research should prioritize: longitudinal case studies of implemented systems. Development of lightweight optimization tools for resource-constrained settings, and Investigation of social acceptance factors in technology adoption. As developing economies account for 90% of global energy demand growth, these optimization strategies will prove decisive in achieving both energy security and climate goals making their continued refinement an urgent priority for researchers and practitioners alike.

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