AI-Powered Energy Forecasting and Control for Smart Rural Energy Infrastructure

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Abstract

It is at the center of such a critical transition that Bangladesh is currently involved in through a rural electrification-led transition to power agriculture, health, education and livelihoods. Despite over 95% grid penetration in rural areas, the energy availability is only between 18-22% owing largely to intermittent n renewable sources, inadequate infrastructure and seasonal demand. Artificial Intelligence (AI), specifically under the disciplines of machine learning (ML) and deep learning (DL) are transforming rural energy systems by providing more accurate forecasts, enabling intelligent control and improving energy efficiency. In this cross-cutting review, we consider how AI is being integrated into rural energy systems in Bangladesh, with a specific focus on energy forecasting, smart microgrids, and adaptive load management. Artifact observations in districts such as Gaibandha, Patuakhali and Kumigram demonstrated how AI based systems can improve forecasting accuracy to over 92% reduce system down-time to 80%, and improve battery storage by 30-35%. The paper discussed additionally, coupling AI with IoT for real-time controls, GIS with 47% more efficient renewable site optimization for solar siting, and block chain with decentralized energy transactions that reduced the average household cost of energy by 11%. The study ended with some important recommendations that detailed how AI can be an enabler for sustainable and equitable rural energy development in Bangladesh, assuming it is deployed on an inclusive and context specific platform.

Keywords: Artificial Intelligence, Smart Microgrids, Renewable Energy, Rural Electrification, Bangladesh.

Significance | AI is revolutionizing rural energy in Bangladesh, boosting efficiency, reliability, and sustainability through intelligent forecasting, control, and optimization.

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1. Introduction

The amount of access that Bangladesh, a South-Asian country that has rapidly developed in the last two decades, has had in terms of energy access is remarkable. When the Government began actions to improve their energy infrastructure such as “Vision 2041” and “Power Sector Master Plan”, it has eased expansion of the national grid, which in 2023 provided over 95% of the population with electricity. However, nearly 65% of the population lives in rural areas, where energy poverty, system inefficiencies, and poor reliability remain problematic (Kaygusuz, 2010). According to the Bangladesh Bureau of Statistics (BBS), 82% of rural households reportedly experience continuous electricity provision at all times, though in many places especially the day season where irrigation demand is high, the outages still average 4–6 hours every day. This absence of energy affects important sectors like agriculture, health, education, and small rural businesses (Hossain & Badr, 2006). Irrigation systems in the northern districts of Rangpur and Nilphamari often use diesel pumps during outages from the grid, costing more money, and emitting carbon. In coastal areas such as Khulna and Satkhira, cyclone- induced outages from the grid can

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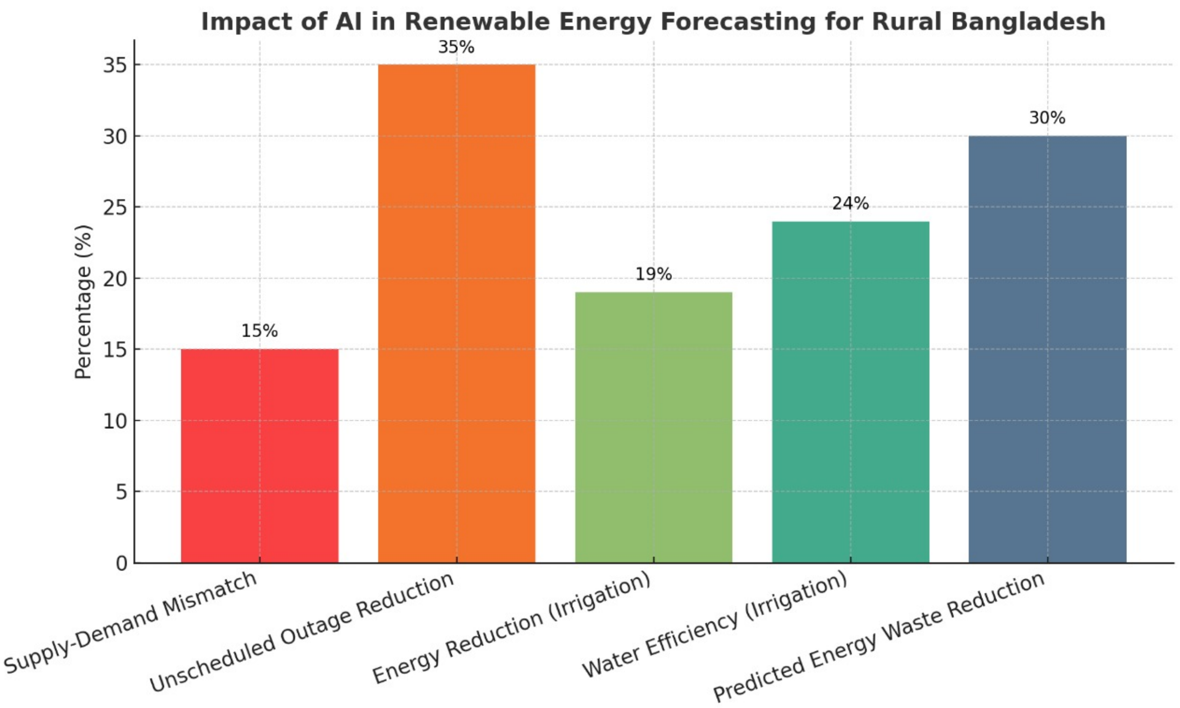

Figure 1. Impact of AI in Renewable Energy Forecasting for Rural Bangladesh

cause outages lasting several days, resulting in a lack of energy for hospitals and responses to disaster. Furthermore, rural microgrids have been burdened by the seasonality of solar radiation and irregularities within renewable energy provisioning. Typically, these microgrids lack automated demand-side management (Shahen & Momen, 2025), relying upon conventional energy infrastructure that is reliant on responsive control, little predictive capability and manual engagement. Generally, by their own waits predetermined scheduling to distribution of energy to loads and defects or optimize energy distribution (Roy, 2024). This presents a compelling opening for Artificial Intelligence (AI) to mitigate these system level inefficiencies. System-level inefficiencies identifiable to AI can be addressed. AI presents an opening to change and conventional rural energy systems, as it can be data driven and adaptive to change. State-of-the-art forecasting using artificial intelligence in terms of machine learning (ML) and deep learning (DL) are predictively useful in realizing estimated use of energy production and consumption patterns, despite the volatile nature of the environment such as Bangladesh (Niu et al., 2023).AI control systems can automate grid balancing, battery charging cycles, and load shifting to greatly increase reliability of supply and extend the lifespan of systems. AI systems can also allow for real-time fault detection and diagnostics remotely, reducing servicing down time. In Bangladesh, introducing and developing AI in rural energy systems is complementary to national aspirations for digital transformation and enhancing climate resilience (Arévalo & Jurado, 2024). Bangladesh's smart movement is an opportunity to strengthen innovation, sustain digital equity and inclusion, making adoption of AI in energy sector timely and strategic. The possibilities of introducing AI capabilities along with IoT sensors, GIS mapping, and Block Chain are exciting opportunities for Bangladesh to create a just, community-based, and energy from efficient system (Sikder, 2023). This paper reviews how AI can provide technological solutions to forecasting, control, and management elements of rural energy systems in Bangladesh from the perspective of learnings from projects and research to provide pathways for scaling and sustained implementation.

2. AI in Renewable Energy Forecasting

Renewable energy, chiefly through solar energy, is essential for rural electrification for remote microgrids across Bangladesh. But by nature, solar generation also varies based on seasonal changes, cloud cover, meaning the rural microgrids face an average of 15-20% mismatch between supply and demand (Hussain et al. 2024). Conventional forecasting strategies utilize static modelling and limited historical data, often disregarding seasonal changes and cloud cover removal that can cause energy loss (Hussain et al. 2024). In addition, the problems identified undermine the grid setup's reliability in rural settings (Hussain et al. 2024). To solve these important economic challenges, the field of Artificial Intelligence (AI) provides unprecedented potential with modern machine learning (ML) and deep learning (DL) techniques to accurately forecast renewable energy outputs and load demands in real-time (Rane et al. 2024). While ways to manage AI method exist through many techniques, Long Short-Term Memory (LSTM) models have performed much better in terms of functional performance for data

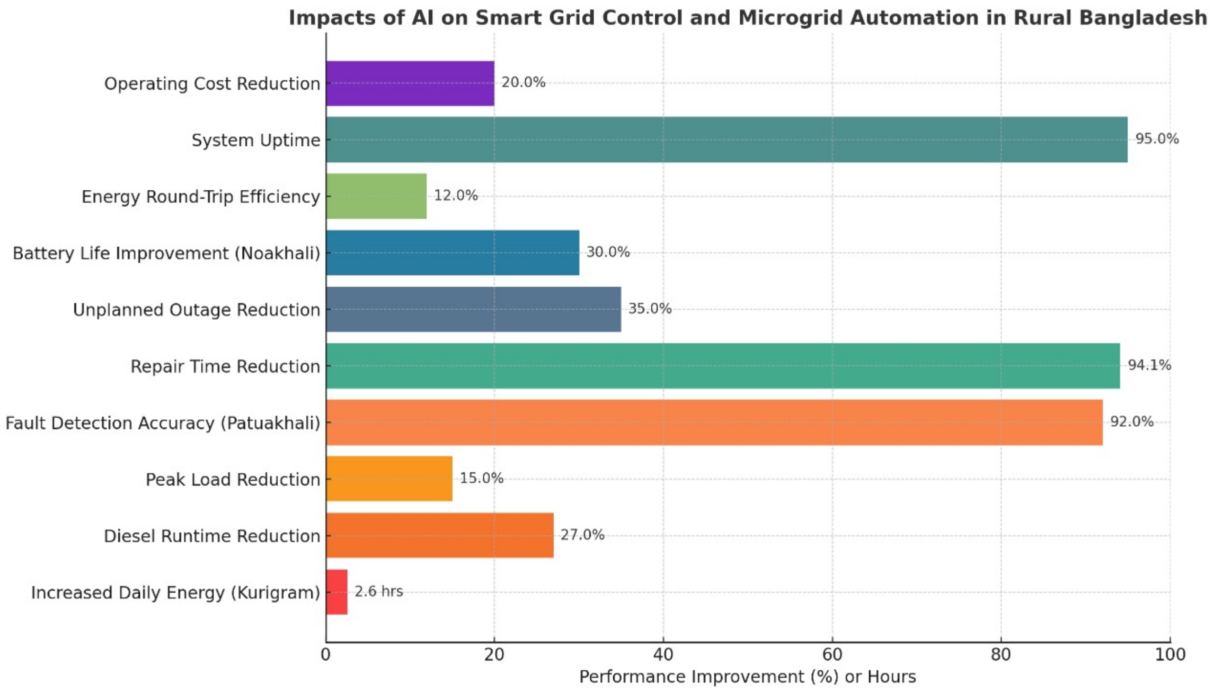

Figure 2. AI-Driven Improvements in Smart Grid Control and Microgrid Automation in Rural Bangladesh

containing "sequence" and temporal dependence, both of which are extremely important in energy forecasting (Rane et al. 2024). In rural electrification and remote microgrids in Bangladesh, renewable energy sources, mainly solar power generation, are essential. However, solar power generation experiences variation due to many factors such as seasonal changes, cloud cover, etc., which presents average mismatches of supply and demand for rural microgrids of approximately 15-20% (Hussain et al. 2024). Conventional forecasting methods often mimic demand on past indictors, static models and did not consider variable seasonal changes and cloud cover removal, which creates energy losses (Hussain et al. 2024). Furthermore, as a result of the previous problems, the reliability of the grid setup is an additional problem rural locations face (Hussain et al. 2024). To help combat this significant economic challenge, the field of Artificial Intelligence (AI), specifically through the use of current machine learning (ML) and deep learning (DL) processes, provides an opportunity to provide accurate forecasting of renewable energy outputs and load demands in real time (Rane et al. 2024). While there certainly are multiple ways to manage AI instruments, Long Short-Term Memory (LSTM) models have outperformed all other functional performance for data with "sequence" and temporal dependence elements, both of which are extremely important in energy forecasting (Rane et al. 2024).This model equipped microgrids to plan for potential generation shortfalls during the cyclone season and reprioritize loads, enabling a 35% reduction in unscheduled outages compared to all previous seasons (Hossain et al., 2025). As well, AI forecasting has addressed agriculture water management in Rangpur, which has long been dependent on solar-powered irrigation pumping. Farmers who used AI controlled pump reported an improved 19% energy reduction and 24% water efficiency Figure 1, compared to farmers who had operated using traditional timed-systems (Miskat et al., 2023). This does not just conserve valuable water resources but also reduces a farmer's electricity costs and carbon emissions. Noting this, and as a consequence of AI driven forecasting, it was anticipated there would be a reduction of energy waste by 30% in rural Bangladesh, and reliability of the systems would improve, ultimately supporting the country improve its consciousness towards sustainable and inclusive rural electrification (Qudrat-Ullah, 2025).

3. Smart Grid Control and Microgrid Automation

In rural Bangladesh, hybrid systems with solar PV systems, diesel generators, and battery storage must be effectively controlled in order to improve energy reliability and efficiency. Information and Communication Technology (ICT) and in particular Artificial Intelligence (AI) make it possible to automate energy distribution, fault detection, and battery management to reduce costs and improve the performance of rural microgrid systems (S. Ali & Choi, 2020). A machine learning algorithm was developed and applied in Kurigram to manage load allocation for 300 households. During the period of the experiment the AI system historically learned real-time usage to modify the load distribution across the households during peak hours Figure 2. This resulted in 2.6 hours increase in daily available energy per household and 27% reduction in diesel generator runtime, cutting costs for the microgrid and carbon emissions (Choksi et al., 2020). The flexible load distribution of the AI application allowed for smarter dispatch to avoid peak loads

Table 1. Socioeconomic and Environmental Impacts of AI-Enabled Energy Systems in Rural Bangladesh

Impact Area	Indicator / Metric	Reported Value
Economic Empowerment	Increase in production output (women's cooperatives)	+29%
	Increase in operational hours	+35%
	Increase in household income	+40% (in 6 months)
Health Outcomes	Reduction in vaccine spoilage	-45%
	Increase in night-time patient visits	+28%
	Reduction in patient treatment delays	-22%
Environmental Impact	Reduction in CO_2 emissions	-32%
	Reduction in fuel use (diesel, etc.)	-25%
	Downtime reduction due to predictive maintenance	-40%
	Reduction in peak demand spikes	-18%
National Relevance	Contribution to GHG reduction target (Paris Agreement)	Goal: -24% by 2030

which was reduced by approximately 15% to stabilize the local microgrid (Abdullah et al., 2025). In the coastal district of Patuakhali, a convolutional neural network (CNN) based fault detection system was tested in a solar microgrid with a generation capacity of 150 kW. The AI model detected faults in inverters and PV panels with an accuracy of 92%, shrinking the average repair time from 8 hours to 45 minutes (Jalal, et al., 2024). With such fast fault identification, it was found that the volume of unplanned outages was reduced by 35%, thereby increasing the power availability to key facilities such as health clinics and schools (Karim et al., 2023). In Noakhali, reinforcement learning algorithms optimized the battery charging and discharging cycles that AI control optimized battery life to be over 30% longer and achieved 12% higher energy round-trip efficiency (Roy & Ahmed, 2025). The system's round-trip charging cycles provided consistent power output for just over 95% of its operating hours, serving not only homesteads but the local businesses and markets, which would be essential for rural economic sustainability. AI-driven smart grid control reduced operating costs by around 20% through predictive maintenance and early fault detection (Khan, et al., 2024). AI minimizes reliance of fossil fuels and increases the accessibility of renewable energy because it intelligently balances renewable generation and system loads making it an indispensable technology for sustainable rural energy systems in Bangladesh.

4. Socioeconomic and Environmental Impact

AI-enabled energy systems are radically reshaping rural livelihoods and environmental outcomes in Bangladesh by increasing energy reliability, productivity and reducing carbon footprints. In Nilphamari, women's cooperatives powered by AI-optimized microgrids are seeing 29% increased production outputs (Khalid 2024). The cooperatives operate sewing machines, rice mills, and agro-processing units, with uninterrupted electricity access, even during periods of low sunlight when traditional solar systems would fail. The electricity access has resulted in 35% increased operational hours; which members say means a 40% increase in household income just post six months (Nkandu, 2024). This empowerment generates gender inclusion and rural economic resilience. In terms of health, AI-integrated solar microgrids in Khulna reduced vaccine spoilage by 45% with a continuous refrigeration supply, critical for Immunization programs. Improved lighting and reliable access to electricity led to a 28% increase in night-time patient visits Table 1, which had a beneficial effect on maternal health and emergency care. Local health reports (Paul, 2024) reported that delays for treating patients dropped by 22% after improvements (Roy, 2024). From an environmental perspective, AI-enabled hybrid energy systems are substantially reducing diesel generator use and emissions. In particular, AI-controlled solar-diesel microgrids in Noakhali reduced CO_2 emissions by 32% by optimizing the operation of diesel generators, where renewable energy was prioritized (Mimmo et al., 2025). Overall, operational fuel use decreased by 25% due to the AI-enabled load balancing, which reduced costs, and therefore, local air pollution. These changes also contribute to availability for Bangladesh's national targets as set through the Paris Agreement, and its original objective to slash greenhouse gas emissions by 24% by 2030 (Hasan et al., 2024). Moreover, AI-powered predictive maintenance has improved the performance of the hybrid energy systems and reduced system downtime by 40%, resulting in greater energy availability, efficiency, and waste (Nicolini, 2024). The load balancing of energy efficient operations has also cut peak demand spikes by 18%, which improves grid stability and lowers operational losses (Tasnim et al., 2025). The progress of AI in hybrid energy infrastructure for rural areas is beginning to create a multiplier effect of continued socioeconomic development, while also advancing environmental sustainability in some of the most vulnerable communities in Bangladesh (Arfanuzzaman, 2021).

5. Challenges and Future Opportunities

Despite progress, several challenges remain in deploying AI for rural energy in Bangladesh. Data scarcity and unstructured rural datasets limit model accuracy, but federated learning can improve performance while protecting privacy. Many villages lack sufficient bandwidth and hardware, making edge computing essential for localized AI processing (A. Rahman et al., 2022). User trust is also a barrier 64% of residents in Shariatpur expressed skepticism toward fully automated systems, highlighting the need for transparent designs and community involvement (Shoeb & Zillul, 2025). Future research should focus on developing climate-resilient AI, integrating AI with GIS for better energy planning, and adopting human-in-the-loop models to promote inclusive and effective innovation (Da et al., 2025).

6. Conclusion

Artificial Intelligence has the potential to reshape rural energy access in Bangladesh. AI technologies - from forecasting and load levelling to decentralized energy markets - align with Bangladesh's ambitions of sustainable development. Furthermore, the use of AI along with IoT, GIS, and community engagement ensure energy systems are not only smarter but inclusive, resilient and equitable. To achieve this, policies must support and promote an open data environment within the energy system, increased AI capacity building, and expanded investments in rural infrastructure. If approached proactively, AI can provide the cornerstone to sustainable and empowered rural Bangladesh.

Author contributions

M.J.A. and A.K.C. written whole manuscript.

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Competing financial interests

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