



Artificial Intelligence-Driven Innovations in Modern Power and Energy Systems: Advancing Efficiency, Resilience, and Green Transition

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Abstract: Artificial Intelligence (AI) is transforming electricity generation, distribution, and consumption by enabling databased decision-making, early problem prediction, and smarter resource management systems [5], [9]. These capabilities improve overall efficiency, strengthen system reliability during disruptions, faults and support the move toward low-carbon content energy sources [12]. This review explores how AI is applied in power circuits. Important applications include deep learning models for predicting different equipment condition [9], multi agent systems for coordinating the electrical grid in real time [10], combined physics and data models for forecasting renewable power output [3], edge computing for fast fault detection, and intelligent scheduling of electric vehicle (EV) charging to reduce peak loads [11]. These AI tools analyze data from phasor measurement units, IoT sensors, smart substations, and distributed energy sources. They help lower outage frequency, minimize energy losses, and allow higher integration of renewable power [12], [13]. Advances between 2025 and 2026 such as agentic AI for independent grid operation [10], federated learning for secure multi-party training, physics-informed neural networks for accurate simulations, and edge AI for very fast control offer exciting potential in all aspects. However, issues like model reliability, cybersecurity threats, and heavy computing requirements still need attention [14]. In India, AI can play a major role in building a reliable and sustainable power sector, especially with rising EV adoption. Success will depend on solving local challenges through practical trial projects, datasets tailored to Indian weather patterns, and test setups for smart EV charging [11], [14]

Keywords: Artificial Intelligence, Power Systems, Grid Reliability, Energy Efficiency, Renewable Energy Integration, Agentic AI, Edge Computing, Predictive Analytics, Federated Learning, Physics-Informed Models, Smart Grids, EV Charging optimization, sustainability.

I. INTRODUCTION

A. Development of AI in Power and Energy Engineering

AI approaches such as supervised learning, reinforcement learning, and hybrid models that combine physical laws with data are helping power systems process large volumes of varied, high-speed data and perform automatic good improvements [3], [9]. The rapid increase in sensor information from phasor measurement units (PMUs), smart and digital meters, drone images, satellite data, and EV usage records has allowed deeper use of AI in power engineering [11]. These systems are effective at early fault spotting using multiple data types, automatic voltage and reactive power controls, grid reconfiguration after disturbances, and scheduling EV charging to match available renewable energy [12]. Technologies including 5G networks, edge computing, and federated learning support decentralized and privacy-protected operations. These are especially suitable for India's diverse grid structures and growing EV numbers [14]. However, difficulties remain, including high training costs, limited ability to apply models to new conditions, and the need for high-quality data. By 2025–2026, agentic AI systems could move grids from simply reacting to problems toward preventing and predictive them, provided that transparency and robustness of system are improved [10].

B. Importance of AI for Better Efficiency, Reliability, and Clean and safe Energy Goals

AI shifts maintenance from fixed schedules to predictive, condition-based strategies [9]. This approach can greatly reduce costs caused by power outages, which often form a large part of utility expenses. AI also optimizes energy flows, keeps voltage levels stable, coordinates EV charging and vehicle-to-grid (V2G) services, and uses digital twins to forecast major failures during extreme weather or high renewable energy penetration [12]. For environmental benefits, AI reduces the uncertainty of solar and wind power with improved forecasts and flexible load management, which decreases wasted energy and emissions [5]. Reported gains, such as 15–30% lower greenhouse gas emissions, vary depending on data quality and system maturity [11]. In India's current context of fast-growing rooftop solar, increasing EVs, and climate challenges, AI-supported virtual power plants and automated distribution

systems show promise. However, careful planning is needed to prevent widening gaps between urban and rural areas, particularly during monsoon seasons.

The partnership between Maharashtra State Electricity Distribution Company Ltd. (MSEDCL) and the Global Energy Alliance for People and Planet (GEAPP) demonstrates this huge potential. It focuses on actual time analytics, battery energy storage systems (BESS), and better renewable integration for improved reliability and cost while also highlighting the need for clear accountability and proper data handling [14].

II. Main AI Applications in Power and Energy Systems

A. Intelligent Optimization and Automatic Dispatch

Hybrid optimization techniques and multi-agent reinforcement learning address uncertain conditions in unit commitment, optimal power flow in the system, and support services [7]. Self-managing AI agents can coordinate microgrids in different load conditions to improve stability and frequency control. Combining blockchain with AI also enables secure peer-to-peer energy trading, including from EVs [10]. Field surveys have reported cost savings of 18–28%. However, results can be changes due to parameter settings and communication delays. In India, where utilities are often fragmented, federated learning methods can help different organizations collaborate safely without creating single points of failure.

B. Advanced Predictive Maintenance for Assets

AI integrates data from vibration sensors, gas analysis, temperature readings, humidity sensors and electrical discharge using models such as long short-term memory (LSTM) networks, autoencoders, and physics-informed networks [9]. This provides reliable estimates of remaining equipment life and helps schedule maintenance more effectively on time[1].

Edge computing delivers quick alerts at the equipment level, which extends asset lifespan and reduces unexpected outages. Challenges include adapting models to different climates and the effort required for regular retraining. In India's hot, humid, and dusty monsoon conditions, sensor performance can decline, making climate-specific adaptations necessary.

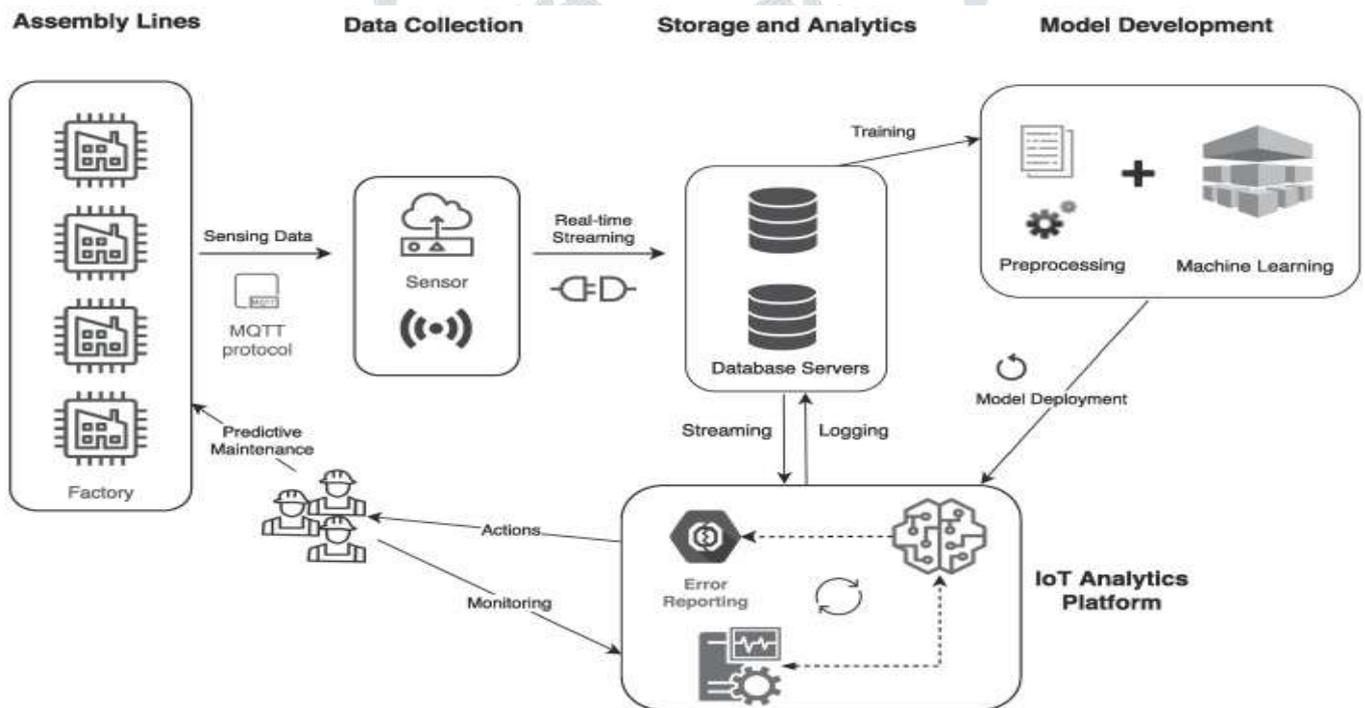


Figure 1: Smart Predictive Maintenance Device/System in Electrical Power Infrastructure

C. Next-Generation Smart Grids

Graph-based neural networks and federated machine learning deliver accurate forecasts of demand (including EV load) across time and location [11]. AI can also identify hidden cyber threats and support self-healing grid functions [12].

By 2025–2026, autonomous agents are expected to manage virtual power plants (VPPs), distributed energy resource systems, and EV fleets even when renewable energy shares are high. Risks include reduced performance with limited data or under attack. India's smart meter program is advancing good, but challenges related to device compatibility and cybersecurity threats must still be addressed [3].

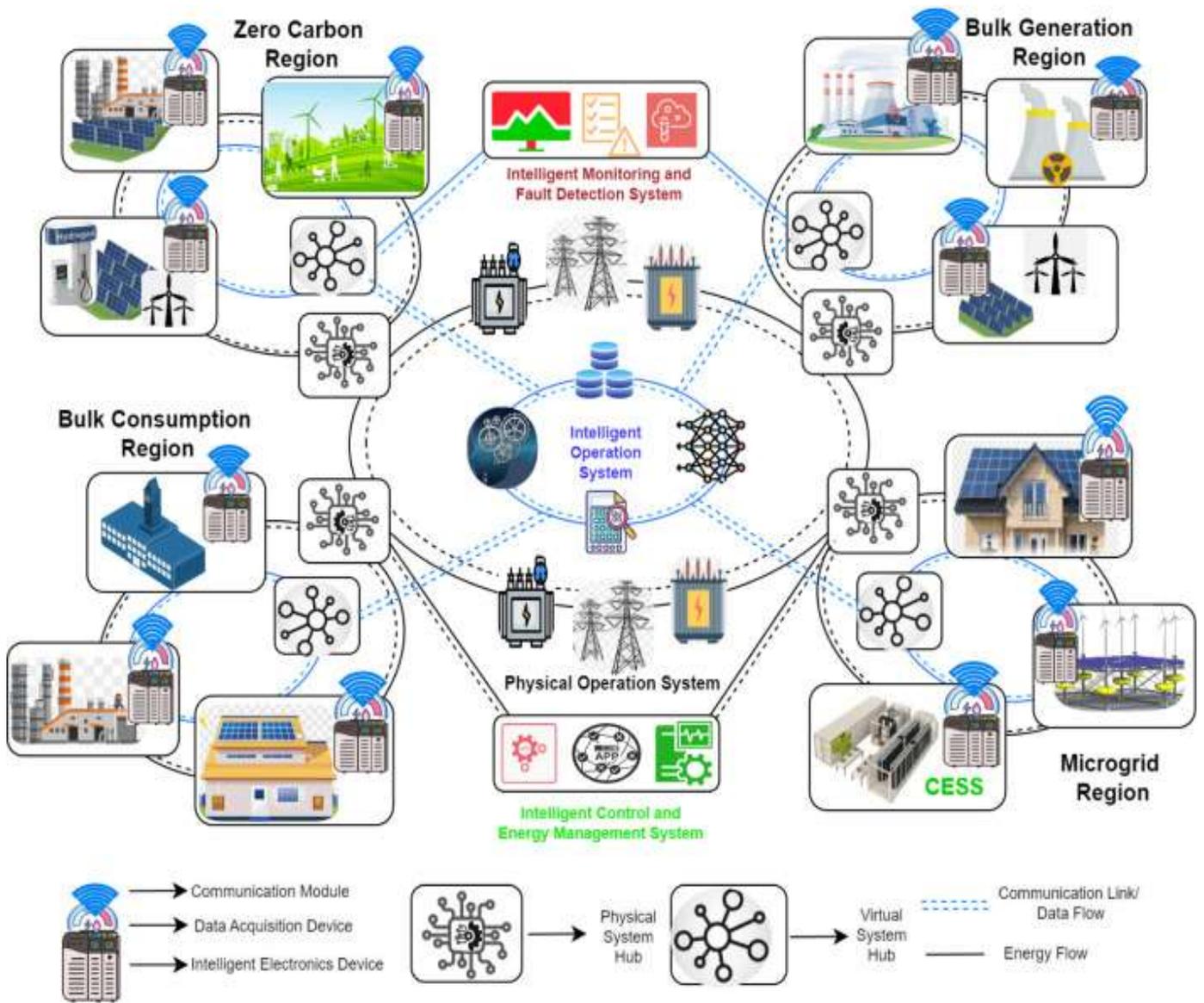


Figure 2: AI-Integrated Smart Grid Ecosystem

D. High-Accuracy Fault Detection and Location

Hybrid models combining wavelets, convolutional neural networks (CNN), and LSTMs with physics-based rules can detect faults quickly and locate them precisely, even in complex grid setups [13]. Physics-informed neural networks improve performance in noisy conditions, which is particularly useful for India’s long rural feeders and grids with many EVs [9].

Training these models can be difficult and computationally demanding. They often need careful tuning and may not perform consistently if the actual grid differs significantly from the training data.

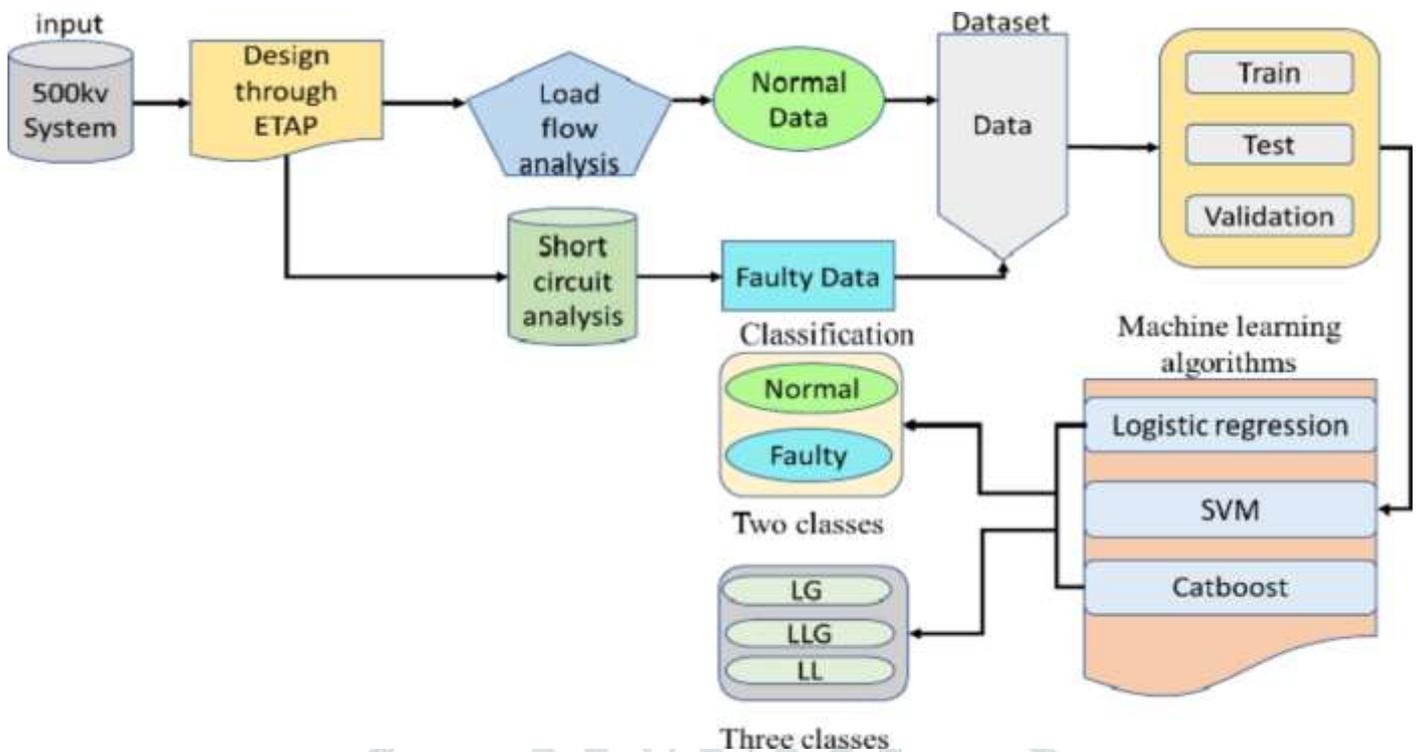


Figure 3: High-Precision Fault Analytics and Localization

III. Enhancing System Performance with AI

AI has been extremely carried out in exceptional regions to improve energy performance:

A. Practical Examples of Performance Improvements

AI helps lower peak load demand in urban and industrial microgrids through forecasting and EV coordination systems [11]. It also optimizes motor drives, building heating ventilation and air conditioning (HVAC) systems, and large-scale energy storage scheduling. In controlled environments, energy savings of 18–40% have been achieved [12].

However, these benefits rely on good data availability and significant initial investment, which can be difficult for smaller Indian utilities. Differences between equipment vendors and proper data governance also affect large-scale adoption [14].

B. Multi-Agent Reinforcement Learning for Demand Flexibility

Multi-agent systems coordinate EVs, household appliances, and industrial loads to shift usage to off-peak periods and better match renewable generation [7]. This can reduce peak demand by 18–35%. Difficulties include training stability when many agents are involved and handling incomplete information about user preferences in India's varied consumer base.

C. AI-Based EV Charging Optimization

Models that combine LSTM networks with deep reinforcement learning schedule charging times, locations, and power levels based on grid conditions, user requirements, and electricity prices [11]. This results in lower costs and emissions compared to unplanned charging. Challenges include errors during periods of low renewable output (such as monsoons) and concerns about protecting user privacy. Ensuring fair access to smart charging facilities in rural parts of India remains an important goal.

IV. Improving Grid Resilience with AI

A. Early Fault Detection

AI continuously analyzes system data to identify emerging faults before they cause major problems [9]. While the approach is fast, noisy conditions in rural Indian networks can lead to false alarms, making a combination of AI and human oversight useful [13].

B. Predictive Analytics for Preventing Failures

AI uses historical and live data to estimate failure probabilities and plan preventive maintenance [9]. Lack of model transparency can reduce operator confidence. In grids with high distributed renewable energy, unexpected events like severe weather can lower prediction accuracy.

C. On Time monitoring and control

Live data streams enable automatic adjustments that reduce outage duration [12]. However, delays in edge-to-cloud communication and cybersecurity risks remain concerns, especially as AI computing itself increases electricity demand on the grid [3].

V Supporting the Green Energy Transition with AI

A. Renewable strength Integration

AI provides better forecasts of solar and wind generation and coordinates energy storage and flexible loads to manage different load conditions [5]. While effective, depending too heavily on data-driven models without physical rules can create instability during unusual events. India's goal of 500 GW renewable capacity by 2030 requires models adapted to local monsoon conditions [12].

B. Minimum Environmental Impact

Efficiency improvements and reduced waste contribute to lower emissions [5]. At the same time, the energy consumed during AI model training and the electronic waste from sensors should be considered to ensure truly sustainable outcomes.

C. Energy Efficiency and Carbon Reduction

AI supports reduced consumption in buildings, industry, and transportation [11]. Without targeted policies, however, benefits may mainly reach urban areas and increase the gap between cities and rural regions in India's clean energy shift [12].

VI. Challenges and Future Directions

A. Ethical Issues: AI introduces concerns around data privacy, fairness in load management decisions, and responsibility when automated actions lead to problems [14]. Clear governance frameworks and regulations are essential, particularly for public utilities such as MSEDCL.

B. Technical Challenge: Major hurdles include insufficient high-quality data, limited explainability of decisions, vulnerability to CYBER-ATTACKS, and difficulty handling real-world variations [9]. In India, reliance on particular vendors and a shortage of skilled professionals further slow widespread adoption [11].

C. Future Trends Promising developments include more advanced maintenance systems, smarter grids, improved renewable energy coordination, and greater automation [10]. Achieving good results will require physics-informed and federated models that perform reliably under India's tropical climate conditions [14].

VII. Summary and Conclusion

AI is introducing intelligent capabilities across all layers of power systems from optimization and maintenance to good control, resilience, and EV integration [3], [9]. It delivers measurable benefits in efficiency, reliability, and sustainability, although actual outcomes depend on careful real-world implementation [11].

Conclusion

AI supports the development of self-managing, flexible, durable and near-zero-emission power infrastructures. Overcoming barriers related to explainability, security, and suitable data especially in grids facing rapid EV growth and climate stresses in India will be critical [14]. The MSEDCL-GEAPP initiative illustrates both the opportunities and the importance of strong governance. Human supervision and ethical safeguards must remain central as AI use expands. Ongoing research will determine whether AI makes clean energy more accessible to everyone or unintentionally increases existing inequalities [11].

Future Scope

Future work should focus on developing explainable AI and physics informed toolkits designed for Indian weather patterns and EV scenarios, building shared open datasets that include monsoon effects and regional EV usage [8], creating blockchain-supported platforms for energy trading among consumers who also produce power through solar or wind, and promoting collaboration across engineering, policy, and other fields [13], [14].

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