International Conference on Artificial Intelligence Research and Applications (ICAIRA)

Prof. Dr. Ilhami COLAK General Chair

September 2-4, 2026, Istinye University, Istanbul, Turkiye

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Topic: AI-Powered Smart Grids: Case Studies and Emerging Solutions for Renewable Energy Integration, Asset Management, and Grid Stability

Abstract

The rapid deployment of renewable energy resources, particularly solar and wind power, is fundamentally reshaping modern electricity grids and accelerating the global transition toward low-carbon energy systems. While large-scale renewable integration supports sustainability and decarbonization objectives, it also introduces significant operational challenges, including generation intermittency, forecasting uncertainty, voltage instability, reduced system inertia, and the growing complexity of managing distributed energy resources. Artificial Intelligence (AI) has emerged as a transformative technology capable of addressing these challenges by enhancing grid intelligence, operational flexibility, reliability, and decision-making capabilities.

This work examines the role of AI-powered energy systems in transforming grid design, planning, and operations in the era of massive renewable energy integration. It explores the application of machine learning, deep learning, reinforcement learning, adaptive neuro-fuzzy systems, and digital twin technologies in renewable energy forecasting, real-time grid monitoring, predictive maintenance, autonomous control, energy storage optimization,

demand-side management, and infrastructure planning. The study further investigates AI-driven approaches for improving grid resilience, voltage stability, fault detection, energy efficiency, and economic performance.

To demonstrate the practical relevance of AI in modern power systems, the work presents representative use cases, AI-driven forecasting models for integrated energy system planning in South Africa, and enhanced adaptive neuro-fuzzy expert systems for predictive voltage-stability monitoring including machine learning frameworks for detecting fraudulent energy consumption patterns in smart meter datasets, optimization-based demand-side management using the Barber Optimization Algorithm for load shifting and peak clipping, AI and digital twin applications for wind turbine monitoring and predictive maintenance, virtualization-based gateway solutions for photovoltaic system integration, These case studies illustrate how AI technologies can support intelligent, data-driven decision-making across diverse energy applications.

The analysis highlights key implementation challenges, including data quality and availability, model explainability, regulatory adaptation, and workforce development requirements. The findings indicate that AI-enabled solutions are becoming essential for maintaining grid stability, reliability, efficiency, and sustainability in highly renewable energy environments. As electricity networks evolve toward decentralized, digitalized, and autonomous architectures, AI is expected to play a foundational role in enabling resilient, economically viable, and sustainable energy transitions worldwide.