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AI-Driven Two-Stage Stochastic Optimization for Autonomous Renewable Microgrids under Uncertainty

C. Marino
Centrum PUCP Graduate Business School
Peru
cmarino@pucp.pe

Abstract

The increasing penetration of renewable energy sources has transformed microgrids into complex cyber-physical systems that require intelligent, adaptive, and automated decision-making. However, the inherent uncertainty of renewable generation—particularly wind and solar—poses significant challenges for reliable and cost-efficient microgrid operation. This paper proposes an AI-driven two-stage stochastic optimization framework that integrates advanced machine learning–based forecasting with operational decision-making for autonomous renewable microgrids. In the first stage, probabilistic forecasts for wind and solar generation are produced using data-driven learning models that capture nonlinear patterns and uncertainty in renewable supply. These forecasts are embedded into a scenario-based stochastic optimization model that determines optimal commitment and dispatch decisions across multiple energy resources, including renewables, battery storage, grid interaction, and conventional backup generation. The second stage adjusts operational decisions in real time as uncertainty is revealed, enabling adaptive and resilient control. A realistic microgrid case study demonstrates that the proposed framework significantly reduces operating costs and renewable curtailment while improving system reliability compared to deterministic and forecast-agnostic baselines. The results highlight how the tight integration of artificial intelligence, stochastic optimization, and automation can enhance digital transformation in energy systems.

Keywords
Artificial Intelligence, Stochastic Optimization, Renewable Energy, Microgrids, Machine Learning, Energy Systems