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THE ROLE OF INDUSTRIAL AUTOMATION IN THE ENERGY TRANSITION: TECHNOLOGIES FOR EFFICIENCY IN POWER PLANTS

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ABSTRACT

The energy transition places new demands on power-generation assets: higher flexibility, tighter integration with variable renewable resources, and continuous pressure to reduce CO_2 emissions and operating costs. Industrial automation—understood broadly as the integration of sensors, distributed controllers, advanced process control and data-driven decision systems—is a practical enabler of that transition. This article argues that modern automation architectures, when combined with real-time control, predictive analytics and digital-twin models, deliver measurable reductions in energy consumption and fuel losses, improve plant ramping performance, and extend equipment life through condition-based maintenance. Evidence from recent literature and applied studies is reviewed to show how high-fidelity sensing and state estimation, advanced regulatory and economic model-predictive controllers, and closed-loop digital twins with real-time orchestration platforms work together to improve efficiency in thermal, hydro and hybrid power plants. The synthesis highlights implementation challenges, such as interoperability, computational requirements and cybersecurity, and suggests pragmatic pathways for staged adoption that prioritize high-impact subsystems and verifiable energy savings.

Keywords: Industrial Automation. Energy Transition. Real-Time Control. Model Predictive Control. Digital Twin. Energy Efficiency. Power Plants.

1 INTRODUCTION

The ongoing transition from fossil-dominated, baseload generation toward a more variable, renewables-rich electricity system forces power plants to operate in regimes for which their original designs were not optimized. Increased cycling, more frequent partial-load operation, and tighter dispatch windows raise thermal inefficiencies and accelerate wear unless control and automation are upgraded. Modern industrial automation reduces these penalties by shortening sensing-to-action loops, enabling optimization on operational timescales, and converting previously offline engineering knowledge into continuous, closed-loop strategies (Heluany et al., 2024).

At the foundation of automation-enabled efficiency are improved measurement systems and state estimation. Advances in sensor technology and distributed instrumentation make it practical to observe temperatures, flows, vibration spectra and combustion parameters with improved spatial and temporal resolution; when combined with online estimation algorithms, these data streams allow controllers to track true process states rather than rely on slow moving setpoints (Buratto et al., 2024). The move from periodic, preventive maintenance to condition-based maintenance founded on real-time diagnostics reduces unplanned outages and avoids efficiency losses due to degraded components.

Control algorithms have also matured. Economic and efficiency-oriented model predictive control (MPC) techniques explicitly optimize plant operation over a moving horizon while respecting constraints and actuator limits, enabling plants to operate nearer to thermodynamic optima even under varying loads (Xu et al., 2024). In practice, MPC and nonlinear MPC implementations have been demonstrated to reduce fuel consumption or improve load-following efficiency in combined-cycle and hybrid generation contexts by predicting future disturbances, such as renewable variability and demand changes, and preemptively adjusting control trajectories (Kestering et al., 2023; Lim et al., 2025).

Digital twins and simulation-connected automation form the third pillar. A digital twin—an online, calibrated model of the plant and its major subsystems—enables rapid virtual experiments, real-time optimization, and anomaly detection without risking physical equipment. Studies indicate that properly implemented digital twins can open optimization margins otherwise inaccessible to fixed rule-based controllers and have been associated with significant energy savings in industrial and building sectors (Heluany et al., 2024; Aghazadeh Ardebili et al., 2024). When a twin is integrated into the control loop, operators can move from corrective to prescriptive strategies: the automation stack proposes setpoints that maximize efficiency while maintaining reliability.

Real-time orchestration across multiple timescales is essential. The energy transition forces interactions across sub-second control (protective relays and governor control), minute-to-hour regulation (load-following and spinning reserve), and day-ahead economic dispatch. Practical automation architectures therefore combine fast regulatory loops with supervisory optimization layers that reconcile short-term efficiency with longer-term economic objectives. Modular, multi-timescale coordinated control strategies have been shown to improve global efficiency in integrated energy systems by coordinating storage, generation and flexible loads in real time, smoothing transitions and avoiding inefficient operating points (Aghazadeh Ardebili et al., 2024).

Machine learning and data-centric automation complement physics-based controls. Supervised and unsupervised learning methods extract latent relationships in historical operational data that support residual-error models for sensors, predictive maintenance classifiers, and demand-oriented schedulers. When ML models are used judiciously, together with physical models and safe fallback control laws, they increase the quality of short-term forecasts and reduce conservative margins that previously degraded plant efficiency. However, ML-driven automation requires careful validation and explainability to meet safety and regulatory constraints in power plant operations (Lim et al., 2025).

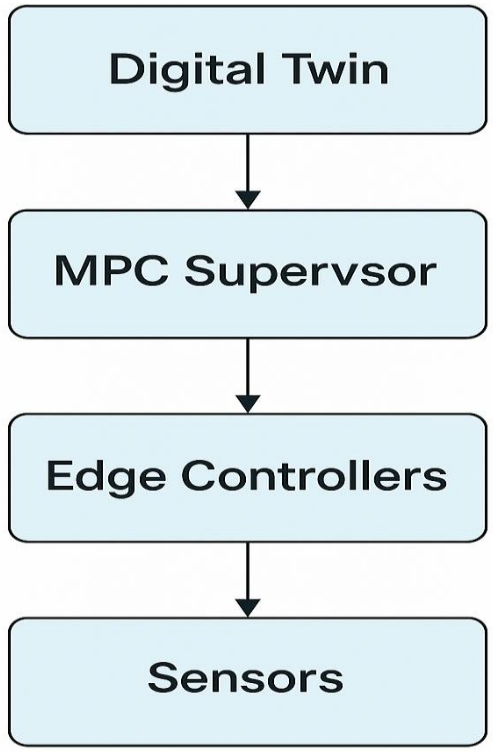
Measured impacts from the literature and pilots are encouraging but context dependent. Reports indicate that digital-twin and predictive control projects can reduce energy consumption and associated emissions by non-trivial percentages—ranging from single-digit to low-double-digit reductions in fuel use or auxiliary power—but results depend on baseline practices, fuel type, and the specific subsystem targeted, such as steam cycle heat rate, boiler combustion tuning, or pump and fan speed optimization (Buratto et al., 2024).

Barriers remain. Interoperability among legacy Distributed Control Systems, Programmable Logic Controllers and modern cloud-native analytics platforms complicates integration; deterministic, real-time execution constraints can strain computational resources for advanced controllers; and cybersecurity concerns are amplified when operational technology is exposed to higher-level networks. Pragmatic deployment strategies therefore prioritize incremental upgrades: sensor retrofits on high-impact equipment, pilot MPC on a controllable subsystem, and deployment of a scoped digital twin for supervisory optimization before enterprise-wide rollouts. Standards, edge computing and hardened communication architectures mitigate many technical risks (Aghazadeh Ardebili et al., 2024).

The flowchart illustrates the hierarchical structure of industrial automation for improving efficiency in power plants, starting from the base with sensors that collect real-time operational data. This information is processed by edge controllers, which execute immediate control actions close to the physical systems. Above them, the MPC (Model Predictive Control) supervisor optimizes operations by forecasting future states and adjusting setpoints accordingly. At the top level, the digital twin integrates data and predictive models to provide a virtual replica of the plant, enabling advanced simulation, anomaly detection, and prescriptive decision-making. Together, these interconnected layers form a closed-loop system that enhances energy efficiency, reliability, and flexibility during the energy transition.

Figure 1

Hierarchical automation architecture for energy efficiency in power plants.



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In conclusion, industrial automation is a central technology vector for decarbonizing and optimizing power generation during the energy transition. By combining improved sensing, efficiency-aware predictive control, and digital twins within a multi-timescale automation architecture, plant operators can reduce energy consumption, lower operating costs and increase flexibility—thereby creating value both for system operators and for decarbonization objectives. Success requires careful selection of high-impact targets, staged implementation, and attention to interoperability and cybersecurity concerns. The literature and recent pilot deployments show that the tools to achieve these gains are mature and ready for application across thermal, hydro and hybrid plants.

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