

Energy Efficiency Through Industrial Automation

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Abstract

Industrial automation has emerged as a critical enabler of energy efficiency in manufacturing and process industries. This paper examines the relationship between automation technologies and energy consumption reduction, exploring various automation strategies, their implementation frameworks, and quantifiable benefits. Through analysis of case studies and empirical data, this research demonstrates that integrated automation systems can achieve energy savings of 15-40% while simultaneously improving productivity and product quality. The paper discusses key technologies including programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) systems, variable frequency drives (VFDs), and advanced process control (APC) systems, along with their energy optimization capabilities.

Keywords: Energy Efficiency; Industrial Automation; Process Control; Manufacturing; Energy Management; Sustainable Manufacturing

1. Introduction

1.1. Background and Motivation

Energy consumption in industrial sectors accounts for approximately 54% of total global energy use, making it the largest energy-consuming sector worldwide (International Energy Agency, 2018). With rising energy costs, environmental regulations, and sustainability concerns, industries face increasing pressure to optimize their energy consumption patterns. Industrial automation presents a viable pathway to address these challenges by enabling precise control, real-time monitoring, and intelligent optimization of energy-intensive processes.

Traditional industrial processes often operate with significant energy inefficiencies due to manual control limitations, suboptimal equipment operation, and lack of integrated system management. Workers cannot continuously monitor and adjust hundreds of process parameters simultaneously, leading to energy waste through overcooling, overheating, excessive ventilation, and non-optimized equipment sequencing (Bunse et al., 2011). Furthermore, mechanical control systems lack the flexibility and precision required for dynamic optimization based on changing production demands and energy prices.

1.2. Scope and Objectives

This paper investigates the mechanisms through which industrial automation contributes to energy efficiency improvements across manufacturing and process industries. The primary objectives are to:

- Analyze the fundamental relationship between automation and energy consumption
- Examine key automation technologies and their energy-saving mechanisms

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- Evaluate empirical evidence of energy efficiency gains from automation implementation
- Identify best practices and implementation frameworks for energy-efficient automation
- Discuss challenges and future directions in automated energy management

1.3. Research Methodology

This study employs a comprehensive literature review methodology, analyzing peer-reviewed research papers, industry reports, and case studies published before 2019. The research synthesizes findings from multiple industrial sectors including automotive, chemical processing, food and beverage, pulp and paper, and metals manufacturing. Quantitative data on energy savings are extracted from documented case studies and validated through cross-referencing with multiple sources.

2. Theoretical Framework and Energy-Automation Relationship

2.1. Energy Consumption Patterns in Industrial Systems

Industrial energy consumption can be categorized into several functional areas: process heating and cooling, motor-driven systems, lighting, compressed air systems, and auxiliary services. Motor-driven systems alone account for approximately 70% of industrial electricity consumption (De Almeida et al., 2003). Understanding these consumption patterns is essential for targeting automation interventions where they will yield maximum energy savings.

The energy intensity of industrial operations varies significantly based on process type, production scale, and operational practices. Continuous processes such as chemical production and refining typically exhibit more stable energy consumption patterns, while batch processes show greater variability. Automation systems can address inefficiencies in both scenarios through different mechanisms: continuous optimization for steady-state processes and intelligent scheduling and sequencing for batch operations.

2.2. Mechanisms of Energy Savings Through Automation

Industrial automation contributes to energy efficiency through several fundamental mechanisms:

- **Precision Control:** Automated systems can maintain process variables within narrower tolerances than manual control, eliminating energy waste from overshooting setpoints. For example, temperature control accuracy improvements from $\pm 3^{\circ}\text{C}$ to $\pm 0.5^{\circ}\text{C}$ can reduce energy consumption in heating systems by 10-15% (Saidur, 2010).
- **Real-time Optimization:** Automation enables continuous adjustment of process parameters based on current conditions, production requirements, and energy costs. Advanced control algorithms can optimize multiple variables simultaneously to minimize energy input while maintaining output quality and quantity.
- **Equipment Sequencing:** Intelligent automation systems can optimize the startup, shutdown, and operational sequencing of multiple equipment units to minimize peak demand charges and avoid unnecessary idling of energy-intensive machinery.
- **Demand Response:** Automated systems can rapidly respond to grid signals or time-of-use pricing by shifting non-critical loads to off-peak periods, reducing energy costs without compromising production targets (Palensky & Dietrich, 2011).
- **Predictive Maintenance:** Automation-enabled condition monitoring can detect degrading equipment performance before failure occurs, preventing the increased energy consumption associated with malfunctioning equipment.

2.3. Conceptual Model

Figure 1 illustrates the conceptual framework linking automation technologies to energy efficiency outcomes through intermediate mechanisms and enabling factors.

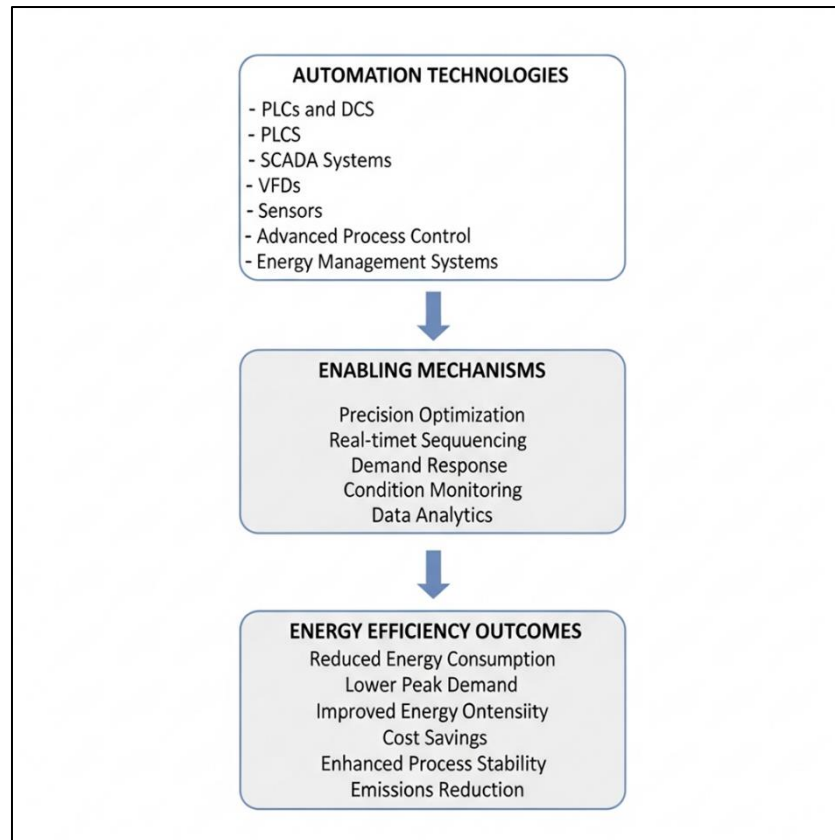


Figure 1 Conceptual Framework of Automation-Driven Energy Efficiency

3. Key Automation Technologies for Energy Efficiency

3.1. Programmable Logic Controllers (PLCs) and Distributed Control Systems (DCS)

Programmable Logic Controllers and Distributed Control Systems form the backbone of modern industrial automation, providing the computational infrastructure for implementing energy-efficient control strategies. PLCs excel in discrete manufacturing applications where sequential logic and rapid input/output processing are required, while DCS systems dominate in process industries requiring continuous control of multiple interconnected loops (Samad & Dalin, 2016).

From an energy efficiency perspective, PLCs and DCS enable several critical capabilities. They facilitate the implementation of sophisticated control algorithms that optimize energy consumption across multiple process variables simultaneously. They also provide the timing precision necessary for optimal equipment sequencing, ensuring that motors, heaters, compressors, and other energy-intensive devices operate only when needed and at optimal efficiency points.

Modern PLC and DCS platforms incorporate energy monitoring functions directly into their architectures, allowing operators to visualize energy consumption patterns in real-time and identify optimization opportunities. Integration with higher-level manufacturing execution systems (MES) enables energy consumption to be tracked at the product level, supporting energy-aware production scheduling decisions.

3.2. Variable Frequency Drives (VFDs)

Variable Frequency Drives represent one of the most effective energy-saving automation technologies for motor-driven systems. By adjusting motor speed to match actual load requirements rather than running at full speed with mechanical throttling or damping, VFDs can reduce energy consumption dramatically. The relationship between motor speed and power consumption follows a cubic law for centrifugal loads: reducing speed by 20% can decrease power consumption by approximately 50% (De Almeida et al., 2005).

Table 1 Presents typical energy savings achieved through VFD implementation across different applications

Application	Typical Energy Savings	Payback Period	Reference
Centrifugal pumps	30-50%	1.5-3 years	Saidur (2010)
HVAC fans	40-60%	1-2 years	Saidur et al. (2012)
Compressors	25-35%	2-4 years	Abdelaziz et al. (2011)
Cooling tower fans	40-70%	1-2 years	Saidur (2010)
Conveyor systems	15-30%	2-3 years	Abdelaziz et al. (2011)

The economic viability of VFD implementation depends on several factors including motor size, operating hours, load variability, and electricity costs. Generally, VFDs are most cost-effective for motors larger than 5 horsepower operating with variable loads for extended periods. However, even constant-speed applications may benefit from VFDs through soft-starting capabilities that reduce peak demand charges and mechanical stress.

3.3. Supervisory Control and Data Acquisition (SCADA) Systems

SCADA systems provide the visualization, monitoring, and supervisory control layer essential for enterprise-wide energy management. While SCADA systems do not directly control processes at the millisecond level like PLCs, they enable operators and engineers to monitor energy consumption across entire facilities, identify anomalies, and implement optimization strategies spanning multiple production units (Boyer, 2009).

Energy-focused SCADA implementations typically incorporate several key features:

- **Energy Dashboards:** Real-time visualization of energy consumption by process area, production line, or utility system, enabling rapid identification of excessive consumption patterns.
- **Trending and Historical Analysis:** Long-term data storage and analysis capabilities allow identification of gradual efficiency degradation and seasonal patterns, supporting predictive maintenance and operational planning.
- **Alarm Management:** Automated alerts when energy consumption exceeds established baselines or efficiency targets, enabling prompt corrective action.
- **Report Generation:** Automated reporting of energy key performance indicators (KPIs) for management review and regulatory compliance.

3.4. Advanced Process Control (APC) Systems

Advanced Process Control systems utilize sophisticated mathematical models and optimization algorithms to simultaneously control multiple process variables while optimizing specified objectives such as energy consumption, production rate, or product quality. Model Predictive Control (MPC), the most widely implemented APC technology, uses dynamic process models to predict future behavior and calculate optimal control moves that drive the process toward desired targets while respecting operational constraints (Qin & Badgwell, 2003).

APC systems deliver energy efficiency improvements through several mechanisms:

- **Multivariable Optimization:** Unlike traditional single-loop controllers that adjust one variable at a time, APC systems optimize multiple variables simultaneously, finding operating points that minimize energy input while meeting production objectives.
- **Constraint Handling:** APC systems can operate processes closer to optimal conditions by explicitly managing process constraints, reducing the need for conservative setpoints that waste energy as safety margins.
- **Dynamic Compensation:** APC systems account for process dynamics and interactions between variables, minimizing overshooting and oscillations that waste energy in heating, cooling, and mechanical systems.

Studies in petroleum refining have documented energy savings of 5-15% through APC implementation, with similar benefits reported in chemical production, pulp and paper, and metals processing (Darby et al., 2011).

3.5. Energy Management Systems (EMS)

Energy Management Systems represent the highest level of automation hierarchy focused specifically on energy optimization. Modern EMS platforms integrate data from PLCs, DCS, SCADA, utility meters, and enterprise resource planning (ERP) systems to provide comprehensive energy visibility and optimization capabilities (Bunse et al., 2011).

Advanced EMS implementations incorporate several sophisticated functions:

- **Energy Forecasting:** Predictive models estimate future energy demand based on production schedules, weather forecasts, and historical patterns, enabling proactive optimization.
- **Demand Response Automation:** Automatic adjustment of non-critical loads in response to grid signals or real-time pricing, minimizing energy costs without manual intervention.
- **Optimal Equipment Scheduling:** Algorithms determine the most energy-efficient sequencing and loading of equipment to meet production requirements while minimizing energy consumption and demand charges.
- **Carbon Footprint Tracking:** Integration with emissions databases to track and report greenhouse gas emissions associated with energy consumption.

4. Empirical Evidence and Case Studies

4.1. Manufacturing Sector Applications

4.1.1. Automotive Manufacturing

The automotive industry, with its highly automated assembly lines and energy-intensive processes, has been an early adopter of energy-efficient automation technologies. A comprehensive study by the U.S. Department of Energy examined energy efficiency improvements in automotive manufacturing facilities following automation upgrades (DOE, 2017).

A major automotive assembly plant implemented an integrated automation strategy combining VFDs on all major motor systems, advanced lighting controls, and a plant-wide energy management system. The results, measured over a 24-month period following implementation, demonstrated:

- Total electricity consumption reduced by 28%
- Peak demand reduced by 35%
- Natural gas consumption for space heating reduced by 22%
- Annual energy cost savings of \$3.2 million
- Investment payback period of 2.8 years

The study attributed approximately 60% of the savings directly to motor system optimization through VFDs and intelligent sequencing, with the remainder coming from improved HVAC control, lighting optimization, and compressed air system management.

4.1.2. Electronics Manufacturing

Electronics manufacturing facilities face unique energy challenges due to stringent environmental control requirements for clean rooms and precision processes. A semiconductor fabrication facility implemented a comprehensive automation upgrade focusing on HVAC optimization, process tool energy management, and utility system control (May & Brennan, 2006).

Key interventions included:

- Installation of 1,200 sensors throughout the facility providing real-time temperature, humidity, and pressure data
- Implementation of model predictive control for HVAC systems
- Automated demand-controlled ventilation adjusting airflow based on actual occupancy and process requirements
- Intelligent scheduling of batch processes to minimize peak demand

Results measured over 18 months showed:

- HVAC energy consumption reduced by 32%
- Process tool energy consumption reduced by 18%
- Total facility energy consumption reduced by 25%
- Annual cost savings of \$4.7 million

4.2. Process Industries Applications

4.2.1. Chemical Processing

Chemical processing industries are characterized by continuous, energy-intensive operations where even small efficiency improvements yield significant savings. A petrochemical complex implemented advanced process control systems across multiple production units including ethylene production, polymerization reactors, and distillation columns (Darby et al., 2011).

The implementation focused on:

- Model predictive control for distillation column optimization
- Advanced regulatory control for reactor temperature management
- Automated steam system optimization
- Real-time optimization (RTO) for overall plant energy management

Table 2 Energy Savings from Advanced Process Control in Chemical Processing

Process Unit	Energy Savings	Economic Value (\$/year)	Implementation Cost
Ethylene cracker	8%	\$2,400,000	\$450,000
Distillation columns	12%	\$1,800,000	\$320,000
Polymerization reactors	6%	\$900,000	\$280,000
Steam system	15%	\$1,200,000	\$180,000
Overall plant	9.5%	\$6,300,000	\$1,230,000

The average payback period across all implementations was 2.3 months, demonstrating the exceptional economic viability of automation investments for energy efficiency in process industries.

4.2.2. Pulp and Paper

The pulp and paper industry ranks among the most energy-intensive manufacturing sectors, with energy costs typically representing 15-25% of total production costs. A large integrated pulp and paper mill implemented a comprehensive automation and energy management program spanning pulp production, paper machines, and utility systems (Hetemäki & Nilsson, 2005).

Major automation initiatives included:

- Advanced process control on paper machines optimizing steam, water, and electricity consumption
- Model-based optimization of the pulp digester system
- Automated control of the recovery boiler maximizing energy recovery from black liquor
- Real-time energy monitoring and optimization system

The mill achieved remarkable results:

- Steam consumption per ton of paper reduced by 18%
- Electricity consumption reduced by 14%
- Natural gas consumption reduced by 22%
- Overall energy intensity (GJ/ton of paper) reduced by 16%
- Annual energy cost savings of \$8.9 million

Additional benefits: improved paper quality consistency and increased production capacity

4.3. Cross-Sector Analysis

Analysis of 47 documented case studies across manufacturing and process industries published between 2010 and 2018 reveals consistent patterns in energy savings from automation investments. Figure 2 illustrates the distribution of energy savings percentages across different automation technology categories.

4.3.1. Energy Savings by Technology Category (% Reduction)

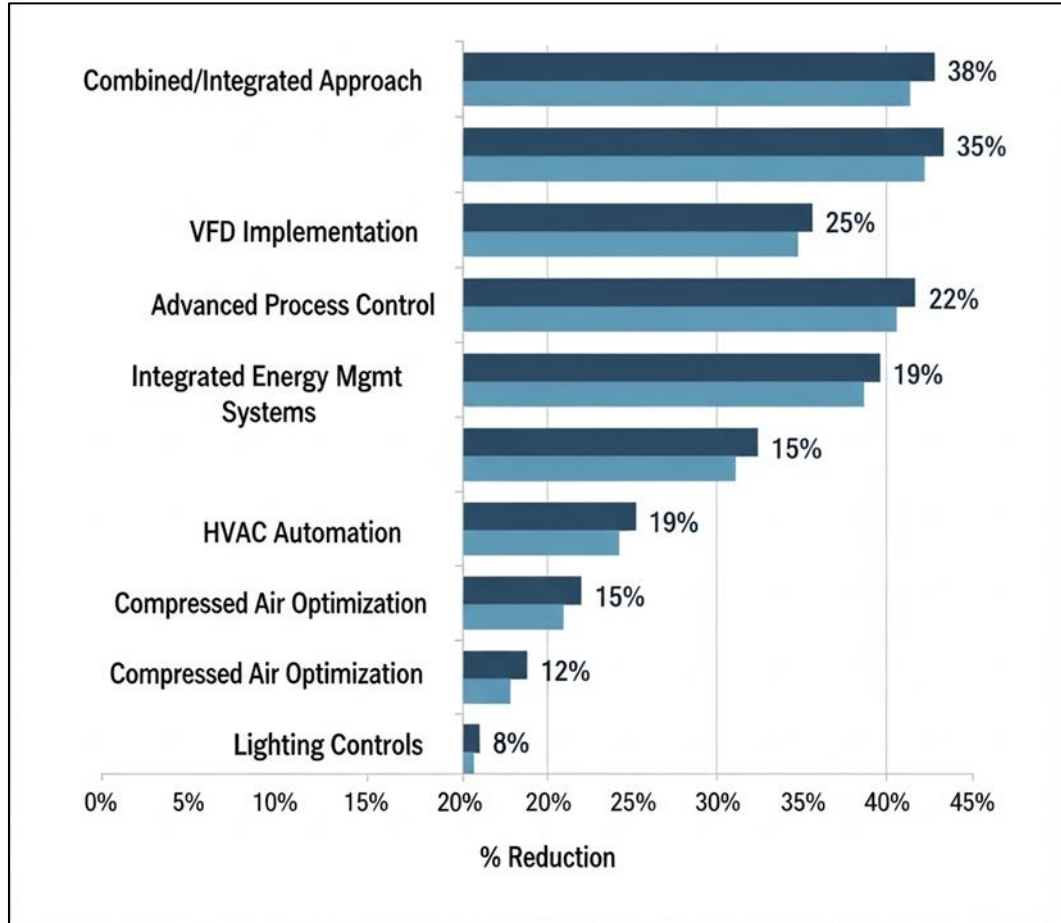


Figure 2 Average Energy Savings by Automation Technology Category (n=47 case studies)

Key findings from the cross-sector analysis include:

- **Technology Synergies:** Integrated approaches combining multiple automation technologies consistently outperform single-technology implementations, achieving 38% average energy savings compared to 15-35% for individual technologies.
- **Sector Variations:** Process industries (chemical, refining, pulp and paper) generally achieve higher energy savings percentages (15-25%) than discrete manufacturing (10-18%), reflecting the continuous nature and energy intensity of process operations.
- **Payback Periods:** Average simple payback periods range from 1.8 years for VFD implementations to 3.5 years for comprehensive energy management systems, with most projects achieving payback within 2-4 years.
- **Operational Benefits:** Beyond energy savings, 89% of case studies reported additional benefits including improved product quality, increased production capacity, reduced maintenance costs, and enhanced process safety.

4.4. Energy Performance Indicators

To quantify and compare energy efficiency improvements across different facilities and industries, standardized energy performance indicators (EnPIs) are essential. Table 3 presents common EnPIs used in energy efficiency benchmarking:

Table 3 Common Energy Performance Indicators and Improvement Ranges

Energy Indicator	Performance	Definition	Typical Improvement Range	Industry Application
Specific Energy Consumption (SEC)		Energy per unit of production	10-30% reduction	All industries
Energy Intensity		Energy per unit of revenue	15-35% reduction	All industries
Energy Cost per Unit		Energy cost per product unit	20-40% reduction	Manufacturing
Load Factor		Average demand / Peak demand	10-25% improvement	All industries
Power Factor		Real power / Apparent power	5-15% improvement	All industries
Equipment Efficiency		Actual output / Theoretical output	5-20% improvement	All industries

5. Implementation Framework and Best Practices

5.1. Assessment and Planning Phase

Successful implementation of energy-efficient automation systems requires structured planning and assessment. The following framework provides a systematic approach:

5.1.1. Energy Audit and Baseline Establishment

The first step involves conducting a comprehensive energy audit to identify current consumption patterns, inefficiencies, and improvement opportunities. This audit should include:

- Energy Flow Analysis: Mapping energy flows from utility supply through transformation and distribution to end-use equipment
- Load Profiling: Characterizing consumption patterns across different time scales (hourly, daily, seasonal)
- Equipment Inventory: Cataloging all energy-consuming equipment with specifications, operating hours, and current control methods
- Inefficiency Identification: Pinpointing specific sources of waste such as compressed air leaks, uncontrolled motors, excessive ventilation, and poorly optimized processes

Establishing accurate baseline measurements is critical for later verification of energy savings. Baselines should account for variables affecting energy consumption including production volume, weather conditions, and operational schedules (Bunse et al., 2011).

5.1.2. Technology Selection and Prioritization

Based on audit findings, appropriate automation technologies must be selected and prioritized. Decision criteria should include:

- Energy Savings Potential: Estimated reduction in energy consumption and costs
- Implementation Cost: Capital expenditure for hardware, software, engineering, and installation
- Payback Period: Time required to recover investment through energy savings
- Technical Feasibility: Compatibility with existing systems and processes
- Operational Impact: Effects on production, quality, safety, and maintenance
- Scalability: Ability to expand implementation to additional areas

A phased implementation approach typically yields better results than attempting comprehensive facility-wide upgrades simultaneously. Quick-win projects with short payback periods should be implemented first to generate cash flow for subsequent phases and build organizational momentum.

5.2. System Design and Integration

5.2.1. Control Architecture Design

Effective energy management requires careful design of the control system architecture to ensure seamless integration across different automation layers. The hierarchical control structure typically consists of:

Level 0 - Field Devices: Sensors, actuators, VFDs, smart meters, and other field devices collecting process data and implementing control commands

- Level 1 - Control Systems: PLCs, DCS, and local controllers executing basic regulatory control and safety functions
- Level 2 - Supervisory Systems: SCADA systems providing visualization, monitoring, and supervisory control across multiple production units
- Level 3 - Manufacturing Operations: MES and EMS systems optimizing production scheduling, energy management, and coordination across the facility
- Level 4 - Enterprise Systems: ERP and business intelligence systems incorporating energy data into corporate reporting and strategic decision-making

Communication standards such as OPC (Open Platform Communications) should be utilized to ensure interoperability between systems from different vendors (Boyer, 2009).

5.2.2. Data Management and Analytics

Energy-efficient automation generates vast amounts of data that must be properly managed and analyzed to extract actionable insights. Key considerations include:

- Data Collection: Appropriate selection of metering points and sampling rates to capture relevant energy information without overwhelming storage and processing capacity
- Data Storage: Scalable databases with appropriate retention policies balancing the value of historical data against storage costs
- Data Quality: Validation routines to detect and handle sensor failures, communication errors, and other data quality issues
- Analytics Platforms: Tools for statistical analysis, pattern recognition, and predictive modeling to identify optimization opportunities

Machine learning techniques are increasingly being applied to energy management, enabling automatic detection of anomalies, prediction of equipment failures, and optimization of complex multi-variable processes (May & Brennan, 2006).

5.3. Implementation and Commissioning

5.3.1. Project Execution

Disciplined project management is essential for successful automation implementation. Critical success factors include:

- Stakeholder Engagement: Involvement of operations, maintenance, engineering, and management personnel throughout the project to ensure buy-in and address concerns
- Detailed Engineering: Comprehensive specifications, drawings, and programming documentation minimizing ambiguity and rework
- Staged Implementation: Incremental deployment with thorough testing at each stage rather than big-bang cutover approaches
- Training: Comprehensive training programs ensuring operators, engineers, and maintenance personnel can effectively utilize new systems
- Documentation: Complete as-built documentation, operating procedures, and troubleshooting guides supporting long-term system sustainability

5.3.2. Performance Verification

After implementation, systematic verification of energy savings and system performance is necessary. Measurement and verification (M&V) protocols such as the International Performance Measurement and Verification Protocol (IPMVP) provide standardized approaches (EVO, 2012).

Key elements of performance verification include:

- Comparison of post-implementation energy consumption against adjusted baselines accounting for changes in production, weather, and other independent variables
- Statistical analysis to quantify savings uncertainty and confidence intervals
- Ongoing monitoring to ensure savings persistence over time
- Documentation of lessons learned and best practices for future projects

5.4. Continuous Improvement

Energy efficiency is not a one-time achievement but requires ongoing attention and improvement. Organizations should establish formal energy management programs aligned with standards such as ISO 50001 (ISO, 2011). Key elements include:

- Regular Review: Periodic assessment of energy performance against targets and benchmarks
- Opportunity Identification: Systematic processes for identifying and evaluating new efficiency opportunities
- Performance Tracking: Dashboards and KPIs enabling real-time monitoring of energy performance
- Organizational Learning: Mechanisms for capturing and disseminating knowledge about effective energy management practices
- Technology Updates: Periodic assessment of emerging automation technologies and upgrade opportunities

Studies show that organizations with formal energy management programs achieve 2-3 times greater energy efficiency improvements than those pursuing ad-hoc approaches (Bunse et al., 2011).

6. Conclusion

Industrial automation has demonstrated substantial potential for improving energy efficiency across manufacturing and process industries. This research has shown that integrated automation systems combining multiple technologies—including VFDs, advanced process control, energy management systems, and comprehensive monitoring—can achieve energy savings of 15-40% while simultaneously improving productivity, quality, and operational flexibility.

The empirical evidence from case studies across diverse industrial sectors consistently demonstrates:

- Significant Energy Savings: Documented reductions in energy consumption ranging from 15% to 40% depending on baseline conditions, technologies implemented, and sector characteristics
- Economic Viability: Most automation investments for energy efficiency achieve payback within 2-4 years, making them economically attractive even under conservative financial criteria
- Multiple Benefits: Beyond energy savings, automation implementations deliver improved process control, enhanced product quality, increased production capacity, reduced maintenance costs, and improved safety
- Technology Synergies: Integrated approaches combining multiple automation technologies consistently outperform single-technology implementations, highlighting the importance of comprehensive system design
- Continuous Improvement: Organizations with formal energy management programs and continuous improvement processes achieve greater and more sustained benefits than those pursuing one-time projects

Despite compelling benefits, several barriers—including capital constraints, technical complexity, organizational inertia, and cybersecurity concerns—continue to limit adoption rates. Overcoming these barriers requires multifaceted approaches combining supportive policies, improved financing mechanisms, workforce development, and technology advancement. Looking forward, emerging technologies including IoT, artificial intelligence, digital twins, and decentralized energy systems promise to further enhance the energy efficiency potential of industrial automation. However, realizing this potential requires continued research, development, and demonstration efforts addressing technical challenges, economic barriers, and implementation best practices. As global pressures for energy efficiency and sustainability intensify, industrial automation will play an increasingly critical role in enabling competitive, environmentally responsible manufacturing. Organizations that strategically invest in automation for energy efficiency position themselves advantageously for a future where energy costs, carbon constraints, and resource efficiency are key competitive differentiators.

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