

Analysis of Production System Automation Effects on Energy Efficiency in Manufacturing Industry

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Abstract: The Brantas River Basin plays a strategic role in supporting domestic, agricultural, industrial, and ecological functions in East Java, Indonesia. Rapid urbanization, land-use change, and increasing anthropogenic activities have exerted significant pressure on river water quality, necessitating comprehensive and reliable assessment methods. This study aims to evaluate the water quality status of the Brantas River using the Pollution Index (PI) approach, which has been widely adopted for river quality assessment in Indonesia and other countries. Secondary water quality data were analyzed, encompassing key physical and chemical parameters, including biochemical oxygen demand, chemical oxygen demand, dissolved oxygen, total suspended solids, nutrients, and selected heavy metals. The PI values were calculated based on Indonesian water quality standards and interpreted according to established classification criteria. The results indicate that most monitoring points along the Brantas River fall into the moderately to heavily polluted categories, reflecting cumulative pollution loads from domestic wastewater, industrial discharges, and agricultural runoff. Comparative analysis with previous studies confirms the consistency of PI-based assessments and highlights spatial variability influenced by land use and human activities. This study demonstrates that the Pollution Index method is an effective and practical tool for evaluating river water quality and provides a scientific basis for pollution control strategies and sustainable river basin management in the Brantas River Basin.

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INTRODUCTION

The manufacturing industry plays a central role in global economic development, value creation, and employment generation. At the same time, it is one of the largest consumers of energy, accounting for a significant proportion of total industrial energy demand worldwide. This dual role places manufacturing at the core of contemporary sustainability challenges, particularly in relation to energy efficiency, environmental impact, and long-term industrial competitiveness. Rising energy prices, increasing regulatory pressure, and global commitments to reduce carbon emissions have intensified the need for manufacturing firms to improve energy performance in a systematic and measurable manner (Benedetti et al., 2015; Xia et al., 2023).

Energy efficiency in manufacturing is not merely a technical issue related to equipment performance, but a multidimensional challenge involving production planning, system integration, operational control, and organizational decision-making. Traditional approaches to energy management have often focused on equipment upgrades or isolated process improvements. While such measures can yield short-term benefits, they frequently fail to address systemic inefficiencies

embedded within production systems, such as idle machine operation, suboptimal scheduling, and lack of real-time energy visibility (Christiansen et al., 2013; Kreitlein et al., 2014). Consequently, there is a growing recognition that structural transformation of production systems is required to achieve sustained energy efficiency improvements.

Production system automation has emerged as a critical enabler of this transformation. Automation technologies allow manufacturing systems to operate with higher precision, consistency, and responsiveness compared to manual or semi-automated systems. According to Matta (2019), automation enables manufacturers to reduce process variability, minimize waste, and improve resource utilization, including energy consumption. By embedding control logic, sensing capabilities, and decision-support mechanisms into production processes, automation creates opportunities to actively manage energy use rather than treating it as a passive by-product of production activities.

One of the primary mechanisms through which automation contributes to energy efficiency is the reduction of non-productive energy consumption. In conventional manufacturing environments, machines often remain powered during idle periods, setup phases, or production interruptions, leading to substantial energy losses. Energy-aware manufacturing environments, as discussed by Bratukhin et al. (2013), integrate automation and monitoring systems to identify and eliminate such inefficiencies. Automated control strategies can selectively power down equipment during non-productive phases and reactivate it when production resumes, thereby reducing unnecessary energy use without affecting output levels.

Scheduling and supervisory control represent another important dimension of automation-driven energy efficiency. Several studies have demonstrated that intelligent scheduling systems can significantly improve energy performance by aligning production activities with energy availability and demand patterns. Chen et al. (2013) show that schedule-based operations enable machines to operate only when required, leading to measurable reductions in idle power consumption. Similarly, Li et al. (2018) emphasize the role of event-based supervisory control in dynamically adjusting machine operation in response to real-time production conditions. These approaches not only improve energy efficiency but also enhance system flexibility and robustness.

Automation-based energy optimization is further strengthened when integrated with networked control and pricing mechanisms. Mechs et al. (2012) propose networked priced timed automata models that incorporate energy pricing signals into production control decisions. Such models allow manufacturing systems to shift energy-intensive operations to periods with lower energy costs, thereby optimizing both energy efficiency and operational expenditure. Complementary research on start-stop automation during non-productive phases confirms the effectiveness of automated control in minimizing energy waste at the system level (Mechs et al., 2013).

The advent of Industry 4.0 has significantly expanded the scope and impact of production system automation. Industry 4.0 frameworks emphasize the integration of cyber-physical systems, industrial internet of things, advanced robotics, and real-time data analytics within manufacturing environments. These technologies enhance energy transparency by enabling continuous monitoring, data-driven analysis, and adaptive control of energy flows across the production system (Mazhar et al., 2025; Klačková, 2025). As a result, energy efficiency becomes an integral component of system design and operation rather than a separate optimization objective.

Empirical evidence suggests that automation and digitalization under Industry 4.0 contribute positively to broader sustainability outcomes. Zhu (2024) demonstrates that robot adoption is

associated with improvements in green economic efficiency, indicating that automation can support both environmental and economic objectives. Morales Rovalino (2025) further highlights that automated manufacturing processes within Industry 4.0 environments enable integrated energy and exergy analysis, facilitating more informed decision-making related to energy use. These findings reinforce the view that automation is a strategic instrument for sustainable industrial development rather than a purely technical upgrade.

Artificial intelligence and expert systems have recently gained prominence as complementary components of automated manufacturing systems. By leveraging large volumes of production and energy data, AI-based systems can identify complex patterns, predict future energy demand, and support proactive energy management. Lu et al. (2022) provide empirical evidence that artificial intelligence significantly improves energy efficiency in manufacturing firms by enhancing predictive control and operational optimization. A systematic review by Ioshchikhes et al. (2024) further confirms that expert systems play a growing role in industrial energy management, particularly in supporting decision-making under uncertainty and complexity.

Despite the extensive body of literature on automation and energy efficiency, existing studies often exhibit fragmentation in terms of technological focus and analytical scope. Many contributions concentrate on specific automation tools, such as scheduling algorithms, robotics, or control architectures, without sufficiently examining their combined and systemic effects on energy efficiency (Christiansen et al., 2013; Kreitlein et al., 2014). In addition, a significant portion of the literature relies on case-specific analyses, which limits the generalizability of findings across different manufacturing contexts and industrial sectors.

Furthermore, while several studies acknowledge the potential of automation to enhance energy efficiency, fewer efforts have been devoted to synthesizing the multidimensional relationships between automation technologies, production system design, and energy performance outcomes. As noted by Benedetti et al. (2015) and Xia et al. (2023), there is a need for integrative perspectives that connect technological innovation with operational and strategic considerations in energy management. Without such integration, the full potential of automation as a driver of energy efficiency may remain underutilized.

In response to these gaps, this study aims to analyze the effect of production system automation on energy efficiency in the manufacturing industry through a comprehensive synthesis of international scientific literature. By systematically examining diverse automation approaches, including control systems, scheduling mechanisms, robotics, Industry 4.0 frameworks, and artificial intelligence, this research seeks to provide an integrated understanding of how automation influences energy efficiency at the production system level. The contribution of this study lies in clarifying the strategic role of automation in achieving sustainable manufacturing and in offering conceptual insights that can inform both academic research and industrial practice.

RESEARCH METHOD

Research Design

This study employs a qualitative descriptive research design based on a structured literature review and analytical synthesis. The qualitative descriptive approach is selected because the objective of the study is not to test hypotheses or generate new empirical data, but to analyze, interpret, and

synthesize existing scientific evidence regarding the effect of production system automation on energy efficiency in the manufacturing industry. This design allows for a systematic examination of patterns, relationships, and conceptual linkages reported across prior studies while preserving the original empirical findings of each source.

A literature-based analytical approach is appropriate for addressing the complexity of automation and energy efficiency, which involves multiple technological dimensions, operational contexts, and system-level interactions. By synthesizing diverse empirical and conceptual studies, the research provides an integrated perspective on how automation technologies contribute to energy efficiency improvements at the production system level.

Data Sources and Selection Criteria

The data used in this study consist of secondary data obtained from peer-reviewed scientific publications, including journal articles, conference proceedings, and scholarly book chapters. The selected literature focuses on production system automation, energy-aware manufacturing, energy-efficient control and scheduling, Industry 4.0, robotics, artificial intelligence, and expert systems in the manufacturing context.

To ensure relevance and academic rigor, several inclusion criteria were applied. First, only publications that explicitly discuss the relationship between automation technologies and energy efficiency in manufacturing systems were considered. Second, the sources were required to be published in reputable scientific outlets and subjected to peer review. Third, the publication period spans from 2012 to 2025, allowing the study to capture both foundational research and recent developments related to digitalization and Industry 4.0. Studies that did not address energy efficiency outcomes or focused solely on non-manufacturing sectors were excluded.

Data Collection Procedure

The literature collection process was conducted systematically by identifying relevant publications through academic databases and publisher platforms commonly used in engineering and industrial research. Keywords such as production system automation, energy efficiency, manufacturing systems, energy-aware manufacturing, Industry 4.0, robotics, artificial intelligence, and expert systems were used to locate relevant studies.

After the initial identification, titles and abstracts were screened to assess their relevance to the research objective. Full-text reviews were then conducted to ensure that each selected study provided substantive discussion or empirical evidence related to automation-driven energy efficiency improvements. Only sources that met all selection criteria were included in the final dataset for analysis.

Data Analysis Technique

The analysis was conducted using a thematic and comparative analytical approach. First, the selected studies were categorized based on the type of automation technology discussed, such as control systems, scheduling mechanisms, robotics, Industry 4.0 frameworks, and artificial intelligence-based systems. This classification enabled a structured comparison across different technological domains.

Second, the reported impacts of automation on energy efficiency were examined and compared across studies. Attention was given to mechanisms such as reduction of idle energy consumption,

optimization of machine operation, real-time energy monitoring, and adaptive control strategies. Rather than quantifying energy savings, the analysis focused on identifying consistent patterns and qualitative relationships reported in the literature.

Third, the findings from individual studies were synthesized to construct an integrated narrative explaining how different automation approaches interact to influence energy efficiency at the production system level. This synthesis emphasizes system integration, operational control, and digital connectivity as key factors shaping energy performance outcomes.

Validity and Analytical Rigor

To enhance analytical rigor, the study relies on multiple sources from different industrial contexts and technological perspectives. Cross-comparison among studies helps reduce bias associated with single-case analyses and strengthens the robustness of the synthesized conclusions. The exclusive use of peer-reviewed literature further supports the credibility and reliability of the analysis.

Research Limitations

This study is limited by its reliance on secondary data and qualitative synthesis. As no primary data or quantitative modeling is employed, the findings reflect patterns and conclusions reported in existing studies rather than direct empirical measurement. Nevertheless, this methodological approach is appropriate for achieving the study's objective of providing a comprehensive and integrative understanding of the effect of production system automation on energy efficiency in manufacturing.

RESULTS AND DISCUSSION

Impact of Production System Automation on Energy Efficiency

The synthesis of empirical findings indicates a consistent positive relationship between production system automation and energy efficiency improvement in manufacturing industries. Across different technological contexts, automation enables more precise control of machine operation, reduces non-productive energy consumption, and enhances the responsiveness of production systems to real-time operational conditions. These effects are reported in energy-aware manufacturing environments, intelligent control systems, and digitally integrated production networks (Bratukhin et al., 2013; Hehenberger et al., 2023).

Automation-driven energy efficiency improvements primarily occur through the reduction of idle energy use and the stabilization of energy consumption patterns. Automated control systems ensure that machines operate only when required, thereby minimizing unnecessary power usage during standby, setup, or interruption phases. This finding is consistently reported across studies examining energy-aware control architectures and automated production environments (Chen et al., 2013; Li et al., 2018).

Energy-Efficient Scheduling and Supervisory Control

Energy-efficient scheduling emerges as one of the most influential automation mechanisms affecting industrial energy performance. Schedule-based and event-driven supervisory control systems dynamically coordinate machine operation according to production demand and system states. Empirical studies demonstrate that such systems reduce peak energy demand and improve

overall energy utilization without compromising production output (Chen et al., 2013; Mechs et al., 2012).

Li et al. (2018) emphasize that event-based supervisory control enables machines to transition between operational states in response to real-time events rather than fixed schedules. This adaptive capability allows manufacturing systems to respond efficiently to production variability while avoiding prolonged idle operation. The convergence of scheduling intelligence and automated control therefore represents a critical pathway for achieving energy efficiency at the system level.

Table 1 presents a synthesis of empirical evidence related to automation-based scheduling and control strategies and their reported energy efficiency impacts.

Table 1. Empirical Evidence on Automation-Based Control and Energy Efficiency

Automation Approach	Key Energy Efficiency Mechanism	Empirical Evidence
Energy-aware control systems	Reduction of idle energy consumption	Bratukhin et al. (2013)
Schedule-based operations	Optimized machine utilization	Chen et al. (2013)
Event-based supervisory control	Adaptive energy use	Li et al. (2018)
Start-stop automation	Elimination of non-productive energy phases	Mechs et al. (2013)

Automation within Industry 4.0 Frameworks

The integration of automation into Industry 4.0 frameworks significantly amplifies energy efficiency outcomes. Industry 4.0 emphasizes interconnected production systems, real-time data exchange, and cyber-physical integration, which collectively enhance energy transparency and control. Digital monitoring systems enable continuous tracking of energy flows, while automated feedback mechanisms support adaptive energy management (Mazhar et al., 2025; Klačková, 2025).

Robotics plays a notable role in this context. Empirical evidence indicates that robot-assisted manufacturing improves process consistency and reduces energy waste associated with manual variability. Zhu (2024) demonstrates that robot adoption contributes to higher green economic efficiency, suggesting that automation supports both energy efficiency and broader sustainability objectives. Morales Roalino (2025) further shows that automated Industry 4.0 environments facilitate integrated energy and exergy analysis, enabling more informed energy-related decision-making.

Role of Artificial Intelligence and Expert Systems

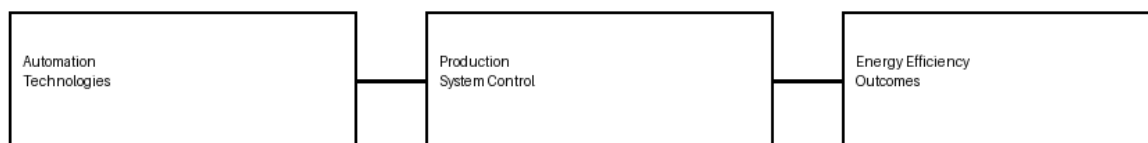
Artificial intelligence and expert systems enhance the effectiveness of automated manufacturing systems by enabling predictive and data-driven energy management. AI-based systems analyze large volumes of operational data to anticipate energy demand, detect inefficiencies, and support proactive control decisions. Lu et al. (2022) provide empirical evidence that artificial intelligence adoption significantly improves energy efficiency in manufacturing firms by optimizing operational processes.

A systematic review by Ioshchikhes et al. (2024) confirms that expert systems are increasingly used to support energy efficiency improvement by assisting decision-making in complex manufacturing environments. These systems complement traditional automation by adding a layer of analytical intelligence, thereby strengthening the link between automation and energy performance.

Integrated Perspective on Automation and Energy Efficiency

Overall, the findings demonstrate that automation influences energy efficiency through interconnected mechanisms rather than isolated technological interventions. Control systems, scheduling intelligence, digital integration, and artificial intelligence collectively shape energy outcomes at the production system level. Figure 1 illustrates the conceptual relationship between automation technologies, production system control, and energy efficiency outcomes based on synthesized empirical evidence.

Figure 1. Conceptual Relationship between Automation and Energy Efficiency Outcomes



These results align with previous studies emphasizing that automation should be viewed as a strategic instrument for sustainable manufacturing rather than solely as a productivity-enhancing technology (Rachman et al., 2025; Wilson et al., 2024). However, the effectiveness of automation depends on system integration quality, organizational readiness, and the alignment between technological capabilities and operational objectives.

CONCLUSION

This study concludes that production system automation has a consistently positive effect on energy efficiency in the manufacturing industry. The synthesis of empirical evidence demonstrates that automation enables more efficient control of machine operation, reduces idle and non-productive energy consumption, and supports adaptive energy management at the production system level. Automated control systems and energy-efficient scheduling mechanisms play a central role in optimizing machine utilization and stabilizing energy consumption patterns.

The findings also indicate that the integration of automation within Industry 4.0 frameworks further enhances energy efficiency outcomes. Digital connectivity, real-time monitoring, and cyber-physical integration improve energy transparency and enable continuous optimization of energy use. In this context, robotics contributes to process consistency and supports improvements in green economic efficiency, reinforcing the strategic value of automation for sustainable manufacturing.

Moreover, artificial intelligence and expert systems strengthen automation effectiveness by enabling predictive, data-driven decision-making. These technologies enhance the capability of manufacturing systems to anticipate energy demand, identify inefficiencies, and implement proactive control strategies.

Overall, the study confirms that automation should be understood not merely as a productivity-enhancing tool, but as a strategic instrument for achieving energy efficiency and supporting sustainable industrial development. Practically, manufacturers are encouraged to adopt integrated automation strategies aligned with digital manufacturing principles and organizational readiness. From an academic perspective, this research provides an integrative framework for understanding the multidimensional relationship between automation and energy efficiency. Future research is

recommended to incorporate quantitative modeling and empirical validation across diverse manufacturing sectors to further substantiate automation-driven energy efficiency improvements.

REFERENCES

- Andrea Matta. (2019). Automation technologies for sustainable production [TC spotlight]. *IEEE Robotics & Automation Magazine*, 26(1), 8–10. <https://doi.org/10.1109/MRA.2019.2892313>
- Benedetti, M., Cesarotti, V., & Introna, V. (2015). Improving energy efficiency in manufacturing systems—Literature review and analysis of the impact on the energy network of consolidated practices and upcoming opportunities. In *Energy efficiency improvements in smart manufacturing systems* (pp. 1–22). IntechOpen. <https://doi.org/10.5772/59820>
- Bratukhin, A., Treytl, A., & Sauter, T. (2013). Energy aware manufacturing environments. In *Proceedings of the IEEE International Conference on Emerging Technologies and Factory Automation* (pp. 1–8). IEEE. <https://doi.org/10.1109/ETFA.2013.6647956>
- Chen, G., Zhang, L., Arinez, J., & Biller, S. (2013). Energy-efficient production systems through schedule-based operations. *IEEE Transactions on Automation Science and Engineering*, 10(1), 27–37. <https://doi.org/10.1109/TASE.2012.2202226>
- Christiansen, L., Linnenberg, T., Fay, A., & others. (2013). Energieeffizienz in der Fertigung bewerten. *atp edition*, 55(7–8), 50–58. <https://doi.org/10.17560/ATP.V55I07-08.262>
- Clark, S. M., Wilson, P. R., & Scott, C. P. (2024). Energy efficiency optimization in mechanical systems: Innovative approaches in industrial applications. *International Journal of Mechanical, Electrical and Computer Engineering*, 1(2), 45–55. <https://doi.org/10.61132/ijmecie.v1i2.76>
- Deepika, C., Taj, K., & Bedar, P. (2024). Automation in production systems: Enhancing efficiency and reducing costs in mechanical engineering. *Nanotechnology Perceptions*. <https://doi.org/10.62441/nano-ntp.vi.3895>
- Hakimzoda, M. M., Safarov, I. M., & Khaliyev, M. S.-U. (2024). Automation and sustainable development impact on resource and energy saving in industry. *Ėkonomika i upravlentie: problemy, rešeniâ*, 11, 70–82. <https://doi.org/10.36871/ek.up.p.r.2024.11.07.001>
- Hehenberger, P., Leherbauer, D., Penas, O., & others. (2023). Holistic system modelling and analysis for energy-aware production: An integrated framework. *Systems*, 11(2), 100. <https://doi.org/10.3390/systems11020100>
- Ioshchikhes, B., Frank, M., & Weigold, M. (2024). A systematic review on expert systems for improving energy efficiency in the manufacturing industry. *Energies*, 17(19), 4780. <https://doi.org/10.3390/en17194780>
- Ioshchikhes, B., Frank, M., & Weigold, M. (2024). A systematic review on expert systems for improving energy efficiency in the manufacturing industry. *Preprints*. <https://doi.org/10.20944/preprints202408.1783.v1>
- Klačková, I. (2025). Energy efficiency of automated manufacturing systems: Innovations, challenges and the future of industrial energy. *MM Science Journal*, 2025(3), 2024109. https://doi.org/10.17973/mmsj.2025_03_2024109
- Kreitlein, S., Rackow, T., & Franke, J. (2014). E|Benchmark—Approaches and methods for assessing the energy efficiency of the industrial automated product manufacturing. *Applied Mechanics and Materials*, 655, 15–22. <https://doi.org/10.4028/www.scientific.net/AMM.655.15>
- Li, Y., Chang, Q., Ni, J., & Xiao, G. (2018). Event-based supervisory control for energy efficient manufacturing systems. *IEEE Transactions on Automation Science and Engineering*, 15(1), 92–103. <https://doi.org/10.1109/TASE.2016.2585679>
- Lu, J., Qian, Y. J., Yang, Y., & others. (2022). Can artificial intelligence improve the energy efficiency of manufacturing companies? Evidence from China. *International Journal of Environmental Research and Public Health*, 19(4), 2091. <https://doi.org/10.3390/ijerph19042091>

- Lu, R., Lu, Y., Chen, Y.-W., & others. (2019). Research on effect on energy efficiency of manufacturing technological progress based on the differential analysis of different kinds of energy-consuming industries. *Journal of Industrial Engineering and Engineering Management*, 33(3), 1–10. <https://doi.org/10.13587/j.cnki.jjeem.2019.03.002>
- Mazhar, S. S., Khan, F. S., Akhlaq, N., & others. (2025). Industry 4.0. In *Advances in environmental engineering and green technologies* (pp. 350–370). IGI Global. <https://doi.org/10.4018/979-8-3693-9471-7.ch019>
- Mechs, S., Müller, J. P., Lamparter, S., & others. (2012). Networked priced timed automata for energy-efficient factory automation. In *Proceedings of the American Control Conference* (pp. 5515–5520). IEEE. <https://doi.org/10.1109/ACC.2012.6315349>
- Mechs, S., Lamparter, S., Peschke, J., & others. (2013). Start-stopp-automatik für nicht-produktivphasen. *atp edition*, 55(6), 34–41. <https://doi.org/10.17560/ATP.V55I06.255>
- Morales Rovalino, V. F. (2025). Análisis energético y exergético de procesos de manufactura automatizados en la industria 4.0: Un enfoque integral. *Polo del Conocimiento*, 10(6), 120–135. <https://doi.org/10.23857/pc.v10i6.9840>
- Rachman, G. A., Saiful, R., Ariati, R., & others. (2025). Energy efficiency strategy in manufacturing industry through implementation of automation technology. *Journal of Mechanical Engineering, Manufactures, Materials and Energy*, 9(1), 1–12. <https://doi.org/10.31289/jmemme.v9i1.13998>
- Wilson, P. R., Clark, S. M., & Scott, C. P. (2024). Energy efficiency optimization in mechanical systems: Innovative approaches in industrial applications. *International Journal of Industrial Innovation in Mechanical Engineering*, 1(2), 30–40. <https://doi.org/10.61132/ijiime.v1i2.61>
- Xia, T., An, X., Yang, H., & others. (2023). Efficient energy use in manufacturing systems—Modeling, assessment, and management strategy. *Energies*, 16(3), 1095. <https://doi.org/10.3390/en16031095>
- Zhu, M. (2024). Maximizing green economic efficiency: The role of robot adoption in shaping the future of manufacturing. *Research Square Preprint*. <https://doi.org/10.21203/rs.3.rs-4005193/v1>