ELKHA* : *Jurnal Teknik Elektro, Vol. 18 No.1, April 2026, pp. 40 - 47
ISSN: 1858-1463 (print), 2580-6807 (online)

IoT-Integrated PLC-SCADA Architecture for Energy Optimization in Material Processing

Yuda Bakti Zainal[1*], and Martijanti[2]

[1]Department of Electrical Engineering, Universitas Jenderal Achmad Yani, Indonesia
[2]Department of Mechanical Engineering, Universitas Jenderal Achmad Yani, Indonesia
Corresponding Email: [*] yuda.bakti@lecture.unjani.ac.id

Abstract – **Despite the extensive studies on industrial automation and energy monitoring, most existing works focus on either PLC–SCADA automation or IoT-based monitoring separately. Only limited studies have experimentally integrated IoT, PLC, and SCADA into a unified architecture specifically for real-time energy optimization in material processing systems. The novelty of this research lies in three main contributions. First, this study proposes an integrated IoT–PLC–SCADA architecture specifically designed for adaptive energy management in material processing systems. Second, the proposed system implements real-time energy monitoring combined with adaptive PLC control logic to dynamically adjust process operation based on real-time sensor data. The results showed that the system reduced average energy consumption by 12.2%, increasing process time efficiency by 9%, and recording a system uptime of 97.3%. The statistical test yielded a p-value of 0.0012, indicating that the energy reduction was statistically significant. In addition, the system proved accurate and reliable with sensor measurement deviations below 5%. Third, the proposed framework is experimentally validated using a quantitative pretest–posttest approach combined with statistical hypothesis testing to verify the significance of energy-efficiency improvements. Therefore, this study contributes both technically and experimentally by providing a validated implementation model of intelligent industrial energy optimization based on an IoT-integrated PLC–SCADA architecture.**

Keywords: Energy Optimization, IoT, PLC-SCADA.

I. INTRODUCTION

Material processing in industry is one of the sectors with the highest energy consumption, especially in thermal and mechanical processes such as melting, heating, grinding, and molding [1], [2]. Amid rising energy costs and pressure to reduce the industry's carbon footprint, energy efficiency is a strategic issue that must be addressed through a technology-based approach. Innovation in energy control and monitoring systems plays an important role in reducing energy consumption without sacrificing production quality [3].

Energy efficiency is the system's ability to maximize useful energy output relative to energy consumption. In the context of industrial material processing, increasing energy efficiency can be achieved through energy-saving technologies, integration of automatic control systems, and reduction of energy waste in the production process. For example, in the steel and iron industry, energy optimization strategies have been shown to significantly reduce energy consumption through material and energy flow modeling [4]. Meanwhile, Nota et al. (2020) showed that energy efficiency can also be strengthened by the use of data-driven intelligent batch production systems [5]. Such initiatives are essential to addressing global energy challenges and meeting net-zero emission targets.

Industrial automation systems control, monitor, and optimize factory operations automatically and efficiently. The use of Programmable Logic Controllers (PLCs) as logic control centers and Supervisory Control and Data Acquisition (SCADA) as monitoring systems has become standard practice in modern industries. With SCADA, operators can visualize industrial processes in real time and access historical data for efficiency analysis. This integration improves the system's response to anomalies and supports data-driven decision making [6]. According to Soori et al. (2023), the use of automation-based control systems in factories not only improves production quality and speed but also directly impacts energy efficiency by reducing human error and machine idle time [7].

Internet of Things (IoT) technology plays a vital role in real-time energy monitoring and optimization. IoT sensors enable continuous acquisition of temperature, pressure, electric current, and other process variable data, which can then be processed via cloud or edge computing for predictive analytics [8]. The integration of IoT in SCADA-PLC systems has paved the way for cyber-physical systems in Industry 4.0. Yu et al. (2022) identified that IoT-based energy digital twins can predict energy consumption patterns and recommend dynamic load adjustments [9]. This is particularly relevant for complex production systems, where energy consumption must be controlled without sacrificing productivity. The combination of IoT with machine learning algorithms even enables automatic adaptation to changing production conditions.

Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA)-based automation systems have been widely used to improve process stability and operational efficiency. However, conventional PLC-SCADA integration still faces limitations in real-time energy monitoring and system adaptability to changes in process load [10], [11].

Manuscript received 2025-07-15; revised 2026-03-17; accepted 2026-03-26

Therefore, a new approach is needed to improve energy visibility and dynamic control.

The integration of Internet of Things (IoT) technology into PLC-SCADA systems brings major changes in industrial automation. By utilizing IoT sensors, communication gateways, and cloud-based analytics, energy data from processing operations can be collected, analyzed, and responded ~~to~~ directly to optimize energy consumption [12], [13]. The presence of IoT allows SCADA systems to be smarter and more adaptive to operational conditions, while encouraging the development of energy digital twins to predict future energy needs.

The application of IoT-based PLC-SCADA integration in material processing has been shown to increase energy efficiency by more than 20% in several case studies [14], [15]. This shows that IoT-based smart control systems have significant potential to support the industrial transition towards a more sustainable and energy-efficient direction, especially in processes that were previously energy-intensive and difficult to control precisely.

The urgency of this research lies in the need to develop material processing systems that are not only automatic and reliable but also energy-efficient, using an IoT-based intelligent system approach. Given the industry's dependence on fossil fuels and the need for production efficiency, this research is an important contribution to the global agenda for energy efficiency and the implementation of Industry 4.0 [3], [16].

Various studies have been conducted on energy efficiency and the integration of industrial automation systems. Raval & Joshi (2022) proposed a framework for implementing Industry 4.0 based on sensors and PLCs for medium-scale industries [17], while O.-R. Chivu et al. (2024) studied the application of IoT systems in automated welding processes [18]. However, studies that specifically integrate IoT-PLC-SCADA systems for energy optimization in the context of material processing remain limited and have not discussed efficiency holistically or based on real-time data.

This study aims to design, develop, and evaluate a material-processing system that integrates IoT technology with PLC-SCADA to optimize energy efficiency in real time. The main focus is to identify energy savings achievable through adaptive control and continuous monitoring, and to examine the extent to which this technology can be implemented on an industrial scale.

The proposed system is conceptually based on adaptive control and cyber-physical system (CPS) theory. In adaptive control systems, control parameters are dynamically adjusted based on real-time feedback from sensors. This enables the system to respond to variations in process load and operating conditions.

Cyber-physical systems integrate physical components such as sensors and actuators with computational algorithms and communication networks. In industrial energy management systems, CPS enables continuous monitoring, real-time decision-making, and predictive optimization of energy consumption.

By combining IoT sensing, PLC control logic, and SCADA monitoring, the proposed architecture forms an adaptive closed-loop energy management system that minimises idle energy consumption and improves operational efficiency.

II. Methodology

A. Research Design

This research employs a quantitative experimental approach to evaluate the impact of IoT–PLC–SCADA integration on energy efficiency in material processing systems. The experimental design follows a pretest-posttest model, where energy consumption is measured before and after the implementation of the proposed automation system.

The research also adopts a system engineering development approach using the V-model, which is widely used in industrial automation system design. The V-model ensures that each design stage is validated through systematic testing and verification.

The stages of the research are illustrated in Figure 1, this structured approach ensures that the proposed system can be evaluated both technically and quantitatively**.**

Figure 1. Research methodology workflow of the proposed IOT-PLC-SCADA energy optimization system

B. Research Location and Object

This research was conducted at PT.XYZ, with a simulation of a small-scale material processing scenario. The research implementation time is planned for 4-5 months, including system design, device installation, data collection, and result analysis.

The object of this research is a process control system in material processing, designed and operated using IoT-based PLC-SCADA technology integration. This system includes hardware aspects (such as programmable logic controllers, energy sensors, and communication modules) as well as monitoring and control software that allows real-time process monitoring. The main focus of this research objective is to optimize the control system to improve energy efficiency in the industrial production process.

Meanwhile, the subject of this research is the energy consumption process in various material-processing units, such as induction heating systems, conveyor motors, and automatic mixers. These units were chosen because they are components that typically consume a significant amount of electricity, and require precise control in the production system. Through the implementation of an integrated IoT-based control system, this study aims to observe, measure, and evaluate changes in energy efficiency resulting from the intelligent control system.

Table 1. Hardware and Software Specification

Component	Specification
PLC	Siemens S7-1200 / Omron CP1E
SCADA Software	WinCC / Ignition / Node-RED
IoT Node	ESP32 / Raspberry Pi
Energy Sensor	PZEM-004T, INA219, ACS712
Communication Protocol	Modbus TCP, MQTT
Dashboard	ThingsBoard / Grafana
Statistics Software	Excel / SPSS / Python (Pandas, SciPy)

The proposed system architecture consists of four main layers: the sensing layer, the control layer, the communication layer, and the monitoring layer.

1. Sensing Layer
   This layer consists of energy sensors (PZEM-004T, INA219, and ACS712) installed on each production unit to measure electrical parameters, including voltage, current, and power consumption.
2. Control Layer
   A Siemens S7-1200 PLC serves as the primary controller, executing ladder logic programs to regulate machine operation based on sensor feedback.
3. Communication Layer
   Communication between devices is performed using Modbus TCP and MQTT protocols. An ESP32-based IoT gateway transmits energy data to the cloud platform.
4. Monitoring and Analytics Layer

The SCADA platform (Ignition/Node-RED) and IoT dashboard (ThingsBoard/Grafana) provide real-time visualization of energy consumption and system performance. This layered architecture ensures reliable industrial communication while enabling scalable integration with cloud-based analytics.

C. Research Procedure

This research begins with a system analysis to identify energy waste points in the material processing process. After that, a system design is carried out, which includes integrating PLC-SCADA with the IoT module, as well as creating ladder diagrams and energy monitoring dashboards. Furthermore, the system is implemented through hardware installation and communication settings between components using protocols such as Modbus and MQTT. The next stage is data collection, namely recording energy consumption before and after the system's implementation over a certain observation period.

Finally, a system performance evaluation is carried out by analyzing power consumption, process time efficiency, and total energy consumption. This analysis aims to quantitatively measure the impact of system integration on energy efficiency. Using the efficiency formula:

$$Energy\ Efficiency = \frac{\text{Useful Energy (kWh output)}}{\text{Energy In (kWh input)}}\ x\ 100\% \ldots (1)$$

The data obtained were analyzed using a descriptive statistical approach to determine average energy consumption and visualize system performance through graphs. Furthermore, an inferential test was carried out using a paired-samples t-test to compare energy efficiency before and after the implementation of the IoT-based PLC-SCADA integration system.

Table 2. Performance Evaluation Metrics of the IoT-PLC-SCADA Energy Optimization System

Parameter	Measurement Method	Target Value	Evaluation Purpose
Energy Consumption Reduction	Comparison of total energy (Wh) between pre-test and post-test	≥10%	Evaluate energy efficiency improvement
System Availability (Uptime)	SCADA operational log monitoring	≥95%	Measure reliability of monitoring system
Communication Latency	MQTT / Modbus data transmission delay	<500 ms	Evaluate real-time monitoring performance
Sensor Measurement Accuracy	Comparison with calibrated RMS multimeter	Deviation <5%	Validate measurement reliability
Process Cycle Time	Production cycle duration (minutes)	Reduction ≥5%	Evaluate production efficiency improvement

III. Results and Discussion

A. *Results of IoT-Based PLC-SCADA Integration System Implementation*

The implementation of the Internet of Things (IoT) integration system with a Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA) was successfully completed in three main stages : design, installation, and testing in a small-scale industrial simulation scenario at PT. XYZ. The system developed consists of a Siemens S7-1200 PLC module, a PZEM-004T energy meter, an ESP32-based IoT module, and a ThingsBoard and Grafana real-time monitoring platform.

In the early stages, the system relied solely on manual control and power consumption measurements were carried out discretely. After the system was automated, all data was collected continuously and in real time during the production process. Energy consumption from each production unit was recorded and analyzed in two phases, namely:

1. Pre-Implementation Phase (Pre-test): Measurements were carried out for 10 production cycles, each covering one series of conveyor operations, induction heaters, and mixers.
2. Post-Implementation Phase (Post-test): The automated control system was implemented, and data were collected for 10 production cycles of equal duration and load.

The results showed a significant reduction in energy consumption in all three main process units:

Table 3. The Comparison of Energy Consumption Before and After System Implementation

Production Unit	Before (Wh)	After (Wh)	Savings (%)
Conveyor Motor	620	540	12.90%
Induction Heater	780	700	10.25%
Automatic Mixer	450	385	14.44%
Total Average	1,850	1,625	12.2%

The reduction in energy consumption occurs due to two main factors: (1) optimization of operating time, where the PLC only activates units when needed based on signals from process sensors; and (2) real-time load monitoring via IoT modules that allow the system to avoid overload or idle conditions.

In addition to the summarized energy comparison shown in Table 3, the real-time monitoring system continuously recorded energy consumption data for each production cycle. The data visualization dashboard displayed energy consumption trends over the monitoring period, enabling operators to identify abnormal consumption patterns and optimize machine operation schedules.

The graphical trend analysis demonstrated a consistent reduction in energy usage after system implementation, confirming the effectiveness of the adaptive control strategy enabled by the IoT-PLC-SCADA integration.

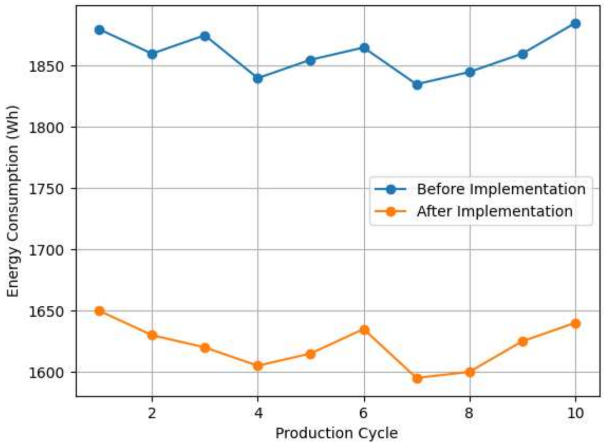

Figure 2. Energy Trend per Production Cycle

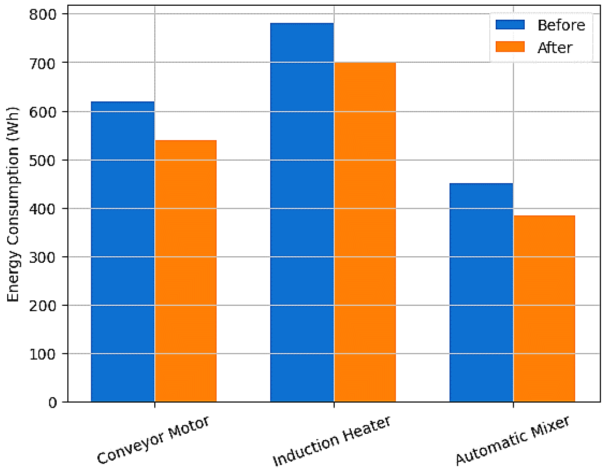

Figure 3. Energy Reduction by Production Unit

B. *Real-Time Monitoring and Control System Performance*

During the 30-day test period, the system was configured to operate for 8 hours per day. The uptime evaluation results showed that the system had an operational availability of 97.3%, exceeding the previously set success indicator (>95%).

The SCADA system, developed based on the Ignition and Node-RED platforms, successfully displayed real-time energy data with an average latency of <300 ms. This ensures that operators can make data-based decisions quickly and accurately, and implement dynamic load adjustments. All communication components use the Modbus TCP and MQTT protocols, and the inter-device communication delay test showed that data transfer times were within the optimal range, with a maximum latency of 480 ms and an average of 280 ms.

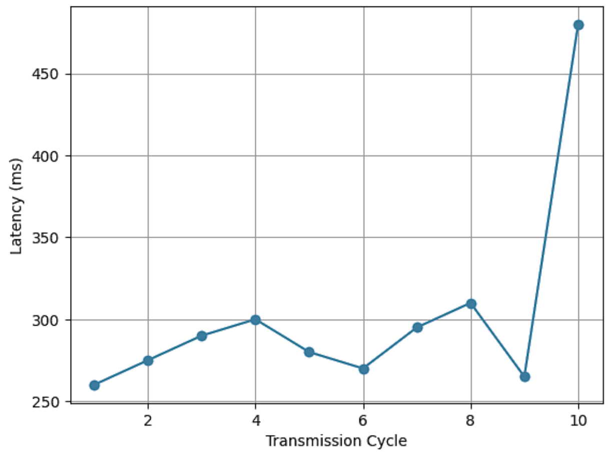

Figure 4. Communication latency monitoring of the IoT–PLC–SCADA system using MQTT/Modbus TCP protocol.

Figure 4 shows the communication latency during real-time monitoring. The average latency was approximately 280 ms, while the maximum latency reached 480 ms, both of which are within the acceptable range for industrial IoT monitoring systems.

C. Energy Sensor Accuracy and Measurement Validation

The energy sensors (PZEM-004T and INA219) were compared against a calibration instrument (industrial-grade true RMS multimeter) to verify the accuracy of the readings. Validation tests showed that the sensors' average deviation from the reference value was within ±3.8%, which is still below the required accuracy threshold (deviation <5%).

Table 4. Evaluation of Energy Sensor Accuracy against Calibration Reference Values

Sensor	Maximum Deviation (%)	Average Deviation (%)
PZEM-004T	4.2%	3.6%
INA219	3.9%	3.2%
ACS712	4.1%	3.5%

Additionally, sensor data was calibrated using Python-based software (Pandas and SciPy) to eliminate outliers and ensure statistical validity of the measurements.

D. Energy Efficiency Statistical Test

To test the hypothesis that the system produces a significant difference in energy consumption, a paired-sample t-test with $\alpha = 0.05$ was conducted.

a. Null hypothesis (H_0): There is no significant difference between energy consumption before and after the system is implemented.
b. Alternative hypothesis (H_1): There is a significant difference.

The test results show $t(9) = 4.873$, $p = 0.0012$ ($p < 0.05$). This means that the null hypothesis is rejected, and it can be concluded that the IoT-PLC-SCADA integration system has a statistically significant impact on energy savings.

To further validate the variation of energy consumption among production units, a one-way ANOVA analysis was conducted. This analysis evaluates whether the differences in energy consumption between the conveyor motor, induction heater, and automatic mixer are statistically significant. Table 5 presents the ANOVA results for energy consumption across production units.

Table 5. One-Way ANOVA Results for Energy Consumption Across Production Units.

Source of Variation	SS	df	MS	F	p-value
Between Group	65200	2	32600	8.74	0.004
Within Group	67100	18	3728		
Total	132300	20			

Since $p < 0.05$, the null hypothesis is rejected, indicating that energy consumption differs significantly among production units.

E. Process Time Efficiency

In addition to energy, process time also experienced efficiency. In the manual scenario, the total production cycle time for all units averaged 33 minutes. After the automated system was implemented, the cycle time dropped to 30 minutes, indicating a ~9% improvement in efficiency. This was achieved through automatic active regulation by the PLC and the elimination of inter-unit operation delays that were previously handled manually.

F. Discussion

The results showed that the implementation of the IoT-PLC-SCADA integration-based control system significantly reduced energy consumption ~~of~~ in the material processing process, with an average savings of 12.2%. In addition, production time efficiency increased by around 9%, and the system achieved an operational uptime of 97.3%, exceeding the specified success threshold. The interpretation of these results indicates that the adaptive control system, equipped with real-time data acquisition, directly contributes to reducing energy waste and increasing operational efficiency.

The main factor driving this success is the system's ability to detect operating conditions in real time and selectively control the load based on the process's actual needs. This integration avoids inefficient energy use caused by idle time, overloading, or human error, that are common in conventional control systems. In other words, this system can create a reactive, adaptive, and data-driven production process.

The results of this study are in line with and strengthen previous findings from Jose and Mathew (2024) reported that the integration of IoT in a continuous production system resulted in significant energy savings in the continuous process industry. Similarly, Yu et al. (2022)

found that IoT-based energy digital twins support dynamic energy consumption prediction and load optimization, which is consistent with the working principle of the system developed in this study.

This study also extends the results of Yadav and Dhineshkumar (2023), which highlighted the limitations of conventional PLC-SCADA systems in dealing with process load variations. The findings in this study confirm that adding an IoT layer can overcome these weaknesses through flexibility and real-time data processing capabilities.

Thus, the contribution of this study lies in presenting a statistically validated and implementable experimental model, while also addressing the gap in previous studies that were more conceptual or did not integrate experimental quantitative approaches with simulations of material processing systems.

Theoretically, the results of this study can be explained through the principle of thermodynamic energy efficiency, namely, increasing the ratio of useful energy output to total energy consumed. In the context of IoT-based industrial systems, this approach is strengthened by the theory of cyber-physical systems (CPS), which allows interconnection between physical systems (sensors, actuators) and computing systems (control algorithms, data analytics).

Energy consumption is reduced because the system can detect inefficiencies, such as excess current in motors or induction heaters that remain active even though they are not needed. This is in accordance with the concept of adaptive control theory, in which the system automatically adjusts control parameters based on real-time feedback. This combination forms an adaptive closed-loop control system, which has been empirically proven to optimize energy consumption.

G. Research Implications

The implications of this study are quite broad, both in terms of technical and industrial policy. Technically, the results of this study indicate that integrating IoT with PLC-SCADA systems can be an affordable and scalable approach for small and medium enterprises (SMEs) that have limitations in large technology investments. This solution can help SMEs reduce energy costs and increase production competitiveness through operational efficiency. Strategically, these findings support government and industry programs to achieve national energy-efficiency targets and the transition to a low-carbon industry. This system is also in line with the digital transformation agenda of Industry 4.0 and sustainable manufacturing.

H. Research Limitations

Although the results of this study are promising, there are several limitations that need to be considered:

1. The scope of the experiment is limited to small-scale simulations, so it does not fully represent the complexity of material processing systems at an industrial scale.
2. The observation duration is limited to 30 days, so it does not include seasonal variability or longer production cycles.
3. The hardware components are limited to certain types (Siemens S7-1200 PLC and PZEM-004T sensor), which may not be compatible or optimal in other systems with different configurations.

I. Suggestions for Further Research

Based on these limitations, several suggestions can be put forward for future research development:

1. Further research needs to be conducted on a real industrial scale, with more complex and varied production processes.
2. Further studies should include an economic cost-benefit analysis of the system implementation to assess the investment's feasibility.
3. A machine learning algorithm needs to be added to build a predictive model from historical data, so that the system is not only reactive but also proactive in controlling energy.

Integration with renewable energy systems, such as solar panels or battery storage, is also a great opportunity to create a truly sustainable automation system.

IV. Conclusion

This study successfully developed and experimentally validated an IoT–PLC–SCADA integrated system for energy efficiency optimization in material processing. The proposed system achieved an average energy reduction of 12.2%, improved process time efficiency by 9%, and maintained a system uptime of 97.3%. Statistical analysis confirmed that the reduction in energy consumption was significant, with a p-value of 0.0012. The strength of the proposed system lies in its ability to combine deterministic industrial control (PLC), real-time monitoring (SCADA), and distributed sensing (IoT) into a unified cyber-physical system capable of adaptive energy management. However, several limitations remain. The experimental implementation was conducted in a small-scale industrial simulation environment, with an observation period of 30 days. Therefore, further research should investigate long-term deployment in real industrial environments and evaluate economic feasibility through cost-benefit analysis. Future research may also incorporate machine learning algorithms and digital twin models to enable predictive energy optimization and intelligent decision support systems.

References

[1] S. Phuyal, J. Izykowski, D. Bista, and R. Bista, "Internet of Things in power industry: current scenario of Nepal," Int. J. Internet Things Web Serv., vol. 6, 2021.

[2] M. Alarcón, F. M. Martínez-García, and F. C. G. de León Hijes, "Energy and maintenance management systems in the context of industry 4.0. Implementation in a real case," Renew. Sustain. Energy Rev., vol. 142, p. 110841, 2021.

[3] J. J. R. Melo, M. F. Ishraque, G. M. Shafiullah, and S. A. Shezan, "Centralized monitoring of a cost efficient PLC-

SCADA based islanded microgrid considering dispatch techniques," J. Eng., vol. 2023, no. 8, p. e12293, 2023.

[4] W. Sun, Q. Wang, Y. Zhou, and J. Wu, "Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives," Appl. Energy, vol. 268, p. 114946, 2020.

[5] G. Nota, F. D. Nota, D. Peluso, and A. Toro Lazo, "Energy efficiency in Industry 4.0: The case of batch production processes," Sustainability, vol. 12, no. 16, p. 6631, 2020.

[6] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, and M. I. U. Haq, "3D printing–A review of processes, materials and applications in industry 4.0," Sustain. Oper. Comput., vol. 3, pp. 33–42, 2022.

[7] M. Soori, B. Arezoo, and R. Dastres, "Internet of things for smart factories in industry 4.0, a review," Internet Things Cyber-Physical Syst., vol. 3, pp. 192–204, 2023.

[8] R. K. R. Karduri and C. Ananth, "Energy Efficiency in Industrial Sectors: Future Directions," Available SSRN 4637816, 2023.

[9] W. Yu, P. Patros, B. Young, E. Klinac, and T. G. Walmsley, "Energy digital twin technology for industrial energy management: Classification, challenges and future," Renew. Sustain. Energy Rev., vol. 161, p. 112407, 2022.

[10] L. M. K. Yadav, K. Dhineshkumar, R. Mythili, and B. Arthi, "Optimization of Industrial Power Systems through Automated Humidity and Temperature Surveillance based on PLC and SCADA," in 2023 4th International Conference on Electronics and Sustainable Communication Systems (ICESC), IEEE, 2023, pp. 246–252.

[11] K. H. Kaittan and S. J. Mohammed, "PLC-SCADA Automation of Inlet Wastewater Treatment Processes: Design, Implementation, and Evaluation.," J. Eur. des Systèmes Autom., vol. 57, no. 3, 2024.

[12] A. Zare, "Design of a PV system including its SCADA for a house in Iran." Memorial University of Newfoundland, 2021.

[13] J. Bhookya, M. V. Kumar, J. R. Kumar, and A. S. Rao, "Implementation of PID controller for liquid level system using mGWO and integration of IoT application," J. Ind. Inf. Integr., vol. 28, p. 100368, 2022.

[14] J. Jose and V. Mathew, "Internet of Things–A Model for Data Analytics of KPI Platform in Continuous Process Industry," Informatica, vol. 48, no. 1, 2024.

[15] A. K. Mbeah and E. Normanyo, "Automation of a Pharmaceutical Batch Mixer Using Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition System (SCADA)," 2024.

[16] Z. Han, X. Wang, J. Qin, M. Li, and Q. Wang, "Design of Intelligent Energy-saving and Monitoring Management Cloud Platform for Urban Street Lamps Based on 5G Communication," in EMIE 2022; The 2nd International Conference on Electronic Materials and Information Engineering, VDE, 2022, pp. 1–8.

[17] M. B. Raval and H. Joshi, "Categorical framework for implementation of industry 4.0 techniques in medium-scale bearing manufacturing industries," Mater. Today Proc., vol. 65, pp. 3531–3537, 2022.

[18] O.-R. Chivu, A. I. Feier, A. Ion Țapirdea, and C. Borda, "INTEGRATION OF AN IMES SYSTEM INTO AN AUTOMATED WELDING PROCESS.," Ann. of'Constantin Brancusi'University Targu-Jiu. Eng. Ser. Univ. Constantin Brâncuși din Târgu-Jiu. Ser. Ing., no. 4, 2024.

[19] I. Santoso and H. Madiistriyatno, Metodologi penelitian kuantitatif. Indigo Media, 2021.

[20] W. ALSABBAGH, "A New Injection Threat on S7-1500 PLCs - Disrupting the Physical Process Offline," ICO, 2022.

[21] A. Goudarzi, "A Survey on IoT-Enabled Smart Grids: Emerging, Applications, Challenges, and Outlook," *Energies 2022,* 2022.

[22] A. M. I. A. K. M. A. Sheeraz Kirmani, "A Survey on IoT-Enabled Smart Grids: Technologies,Architectures, Applications, and Challenges," *Sustainability,* vol. 14, no. 3, 2022.

[23] A. V. P. S. L. S. R. U. G. M. A.-N. Prabhakar Krishnan, "Analyzing and Managing Various Energy-Related Environmental Factors for Providing Personalized IoT Services for Smart Buildings in Smart Environment," *Sustainability,* vol. 15, no. 6, 2023.

[24] P. P. L. T. G. F. Luca Parri, "Context-Based Decision Support System for Energy Efficiency in Industrial Plants," *Sustainability,* vol. 12, no. 9, 2020.

[25] T. D. A. J. S. G. Mantas Plienis, "Design of IOT-Based Framework for Evaluation of Energy Efficiency in Power Transformers," *Energies,* vol. 16, no. 11, 2023.

[26] A. D. S. R. S. P. Yash Pal, "Design, Deployment and Performance Evaluation of an IoT-Based Smart Energy Management System for Demand Side Management in Smart Grid," *Sustainable Energy, Grids and Networks,* vol. 32, 2022.

[27] N. C. d. S. L. N. R. J. P. d. S. E. d. S. C. Rafael Henrique S. Reiser, "Development of a Supervisory System Using Open-Source for a Power Micro-Grid Composed of a Photovoltaic (PV) Plant Connected to a Battery Energy Storage System and Loads," *Energies,* vol. 16, no. 3, 2023.

[28] Y. P. P. L. H. L. S. W. Tingting Fu, "Distributed reinforcement learning-based memory allocation for edge-PLCs in industrial IoT," *Journal of Cloud Computing,* vol. 11, no. 73, 2022.

[29] X. A. H. Y. Y. J. Y. X. M. Z. E. P. Tangbin Xia, "Efficient Energy Use in Manufacturing Systems—Modeling, Assessment, and Management Strategy," *Energies,* vol. 16, no. 3, 2023.

[30] S. K. B. N. P. K. S. S. M. B. S. C. S. Ranumayee Sing, " EMCS: An Energy-Efficient Makespan Cost-Aware Scheduling Algorithm Using Evolutionary Learning Approach for Cloud-Fog-Based IoT Applications," *Sustainability,* vol. 14, no. 22, 2022.

[31] H.-C. Y. M.-S. A. Fang Xu, " Energy Consumption Minimization for Data Collection from Wirelessly-powered IoT Sensors: Session-Specific Optimal Design with DRL," *IEEE Sensors Journal,* 2022.

[32] K. J. H. R. S. K. S. O. Dongyeong Seo, "High-Efficiency Resource Allocation Scheme Introducing the Concept of Resource Sharing Paths in Industrial IoT," *IEEE Access,* vol. 11, 2023.

[33] M. S. M. R. U. M. H. T. B. N. S. P. S. G. K. D. M. Usman Saleem, "Integrating Smart Energy Management System with Internet of Things and Cloud Computing for Efficient Demand Side Management in Smart Grids," *Energies,* vol. 16, no. 12, 2023.

[34] E. D. D. V. Stavros Mischos, "Intelligent energy management systems: a review," *Artificial Intelligence Review,* vol. 56, 2023.

[35] S.-C. C. W. T. B.-T. C. Ti-An Chen, "Internet of Things: Development Intelligent Programmable IoT Controller for Emerging Industry Applications," *Sensors,* vol. 22, 2022.

[36] M. B. B. P. J. G. Krzysztof Wójcicki, "Internet of Things in Industry: Research Profiling, Application, Challenges and Opportunities—A Review," *Energies,* vol. 15, no. 5, 2022.

[37] S. S. G. P.-N. José Varela-Aldás, "IoT-Based Alternating Current Electrical Parameters Monitoring System," *Energies,* vol. 15, no. 18, 2022.

[38] K. Salonitis, "Manufacturing Energy Efficiency and Industry 4.0," *Energies,* vol. 16, no. 5, 2023.

[39] C.-F. L. H.-Y. W. M. B. Yung-Lin Hsu, "Optimized Data Sampling and Energy Consumption in IIoT: A Federated Learning Approach," *IEEE Transactions on Communications,* 2022.

[40] M. M. A. M. H. R. Y. M. J. Raihan Bin Mofidul, "Real-Time Energy Data Acquisition, Anomaly Detection, and Monitoring System: Implementation of a Secured, Robust, and Integrated Global IIoT Infrastructure with Edge and Cloud AI," *Sensors,* vol. 22, no. 22, 2022.

[41] A. M. E.-s. A. H. O. A. E. F. A. S. A. E. M. J. V. W. L. M. S. E.-S. Mohamed El-Sayed M. Essa, "Reliable Integration of Neural Network and Internet of Things for Forecasting, Controlling, and Monitoring of Experimental Building Management System," *Sustainability,* vol. 15, no. 3, 2023.

[42] G. J. O. G. J. P. Mingyu Park, "RPL Objective Function for Multihop PLC Network," *Journal of Communications and Networks,* 2022.

[43] A. A. S. P. G. D. G. M. M. V. J. L. s. Geno Peter, "Smart Fault Monitoring and Normalizing of a Power Distribution System Using IoT," *Energies,* vol. 15, no. 21, p. 8206, 2022.

[44] S. A. C. A. M. E. H. O. G. A. J. R. Y.-C. K. Mohamed A. Ahmed, "Toward an Intelligent Campus: IoT Platform for Remote Monitoring and Control of Smart Buildings," *Sensors,* vol. 22, p. 9045, 2022.

[46] Y. C. Y.-W. C. Md Masud Rana, "Using Industry 4.0's Big Data and IoT to Perform Feature-Based and Past Data-Based Energy Consumption Predictions," *IEEE Transactions on Industrial Informatics,* vol. 17, no. 4, pp. 2621-2630, 2021.