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Original Article

# Development of Energy Monitoring System for Container-Type Plant Factory

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## Abstract

This paper presents the development of an intelligent, web-based energy monitoring system for container-type plant factories, aimed at optimising energy consumption and promoting sustainability in controlled-environment agriculture. The system integrates the Internet of Things (IoT) and Industry 4.0 technologies to provide real-time energy monitoring and control across subsystems such as lighting, climate control, and irrigation. A comparative analysis of the sensor-based system and a fixed control strategy showed that the sensor-based system significantly reduced energy consumption, achieving savings of approximately 1.27 kWh/day without compromising thermal comfort. Statistical analysis revealed a mean energy consumption of 7.41 kWh for the sensor-based system, compared to 8.68 kWh for the fixed system, indicating higher efficiency and flexibility. Economic evaluation demonstrates the financial viability of the system, with an estimated payback period of 4.3 years and a return on investment (ROI) of 131% over a 10-year period. This positions the system as a cost-effective solution for small to medium-scale plant factories, supporting broader sustainability goals by reducing operational costs and carbon footprints, in alignment with the Energy Efficiency and Conservation Act (EECA) 2024. The system also incorporates robust reliability and security features, including redundancy in key components, automated fault diagnosis, and end-to-end encryption, ensuring long-term operational stability. This study highlights the potential of IoT-enabled energy monitoring to enhance sustainability in agriculture, providing a scalable, economically feasible solution for the future of food production. Future work will focus on integrating renewable energy sources and predictive analytics to further optimise energy management.





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Plant Factory

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## 1. Introduction

The development of intelligent energy monitoring systems in plant factories marks a significant step toward optimising energy consumption and enhancing sustainability. These systems leverage recent technological advancements, particularly within the framework of Industry 4.0, to enable real-time surveillance and control of energy usage and production processes [1]. By integrating the Internet of Things (IoT) and advanced data analytics, manufacturers can gain access to previously unavailable data, empowering data-driven decision-making in energy management [2].

To implement these systems effectively, a comprehensive strategy is required, including process integration, data analysis, and management [3]. Integrating energy analysis into existing production systems ensures that energy consumption is monitored alongside production metrics, which enables the identification of optimisation opportunities [4]. This approach not only provides real-time insights but also fosters a culture of sustainability by meeting regulatory standards and promoting corporate social responsibility [5]. For instance, companies implementing energy-efficient practices can enhance their reputation, attracting environmentally conscious investors and consumers [6].

Energy load balancing, supported by cloud and fog computing, offers a more reactive and flexible energy management approach [7]. This paradigm facilitates the efficient use of distributed energy resources, enhancing network stability and improving energy savings [8]. As energy storage systems become more widespread, intelligent energy monitoring will also support the integration of renewable energy sources, creating a more resilient and sustainable energy ecosystem [9].

Container-type plant factories, which are increasingly being adopted in controlled-environment agriculture, face significant challenges in managing energy consumption. These facilities often rely on multiple energy-intensive systems, such as lighting, climate control, and irrigation, leading to high energy costs and inefficiencies without effective monitoring. Many such facilities lack comprehensive, real-time energy monitoring systems, which limits the ability to optimise energy usage, resulting in wasted resources and higher operational costs. Hence, an advanced energy monitoring system that provides accurate, real-time insights into energy consumption is essential to improve efficiency, reduce costs, and support sustainability in these environments.

The design and implementation of intelligent energy monitoring systems in plant factories represent a substantial advancement, particularly in agriculture. These systems not only optimise energy consumption but also incorporate sustainability practices that align with broader environmental goals. As the agricultural sector increasingly adopts IoT technology, which reflects Industry 4.0 capabilities, the potential for improving energy efficiency and sustainability continues to grow, paving the way for widespread adoption [10].

In recent years, energy monitoring and management systems in agriculture have gained momentum, driven by the demand for sustainability, resource efficiency, and climate-smart farming practices. The adoption of technologies such as wireless sensor networks (WSN), IoT platforms, and data-driven monitoring tools has expanded, enabling real-time tracking of energy consumption across various agricultural systems, including irrigation, lighting, HVAC, and climate control. These technologies allow farmers to detect inefficiencies, reduce energy waste, lower operational costs, and decrease greenhouse gas emissions, contributing to the global push toward decarbonisation and sustainable food production [11]. However, there are still significant regional differences in energy efficiency, with regions like Europe demonstrating higher energy-use efficiency than others, such as parts of Asia and Africa, which are still working toward these improvements.

While existing energy monitoring systems provide valuable insights, they often face limitations, such as offering only aggregate data, lacking flexibility, and struggling with integration across various energy sources. Many of these systems are also costly, rigid, and challenging to scale, especially in specialised environments like container-type plant factories. To address these challenges, energy monitoring systems designed for controlled-environment agriculture represent a key innovation. These systems meet the unique energy demands and control requirements of high-tech, intensive farming operations, overcoming the limitations of traditional monitoring solutions. By offering more detailed, real-time insights and greater flexibility, our system aims to enhance energy efficiency, reduce operational costs, and support the sustainability goals of modern agricultural practices [11].

This paper will discuss the process of developing a web-based energy monitoring system for a container-type plant factory, focusing on optimising energy usage and promoting sustainable crop production in a controlled environment.

## 2. Materials and Methods

This study was conducted to develop an integrated energy monitoring and control system specifically designed for air conditioning (AC) units and LEDs within a container-type plant factory environment. The methodology consists of five main phases: system design, hardware integration, dashboard and user interface development, control logic implementation, and system testing and validation. Each phase was carefully structured to ensure system reliability, energy efficiency, and environmental suitability for plant growth.

### 2.1. System Design and Requirements Analysis

In controlled environments such as container-type plant factories, AC units and lighting systems constitute the largest portions of overall energy consumption. AC units are essential for regulating temperature and humidity to maintain optimal growing conditions, but they demand substantial energy, especially during periods of high cooling load. Similarly, lighting, particularly when using high-intensity grow lights for photosynthesis, contributes significantly to operational energy usage due to long operating hours and high-power requirements. These two components together often represent the core drivers of energy cost in plant factories. The developed energy monitoring system directly addresses these challenges by providing real-time tracking of energy consumption for both AC units and lighting systems. Through detailed, subsystem-level insights, the system enables operators to identify inefficiencies such as unnecessary cooling cycles or overuse of lighting, optimise operating schedules, and adopt energy-saving strategies. This targeted monitoring supports better decision-making, reduces total energy consumption, and enhances the overall sustainability of container-type plant factory operations. A modular system architecture, as shown in Figure 1, was designed to support scalability and integration with existing infrastructure.

The energy monitoring system utilises two key technologies: Modbus RTU and LoRa. Modbus RTU is used for communication between energy monitoring devices, such as sensors and energy meters. This reliable and cost-effective protocol allows for real-time data collection from critical systems like lighting and HVAC, facilitating seamless integration and efficient monitoring. LoRa (Long Range) is employed for long-range, low-power communication. It transmits energy data over distances of several kilometres, making it ideal for large agricultural environments. LoRa's low power consumption extends battery life, reduces maintenance, and ensures scalable, cost-effective monitoring. Together, Modbus RTU and LoRa enable efficient, real-time energy monitoring across expansive agricultural setups.

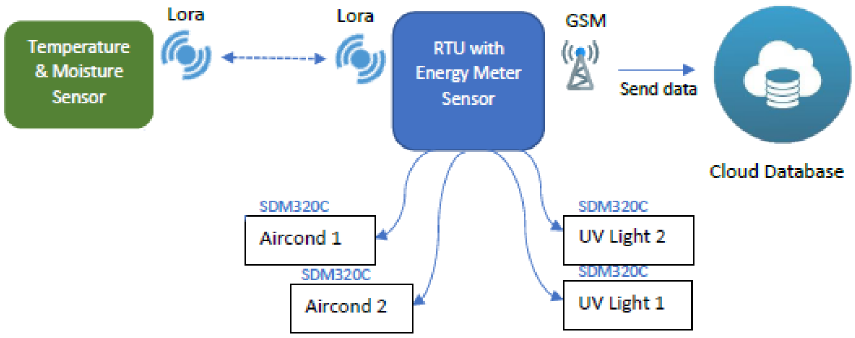



**Figure 1.** System architecture.

### 2.2. Hardware Selection and Integration

Appropriate hardware components were selected to monitor and control the AC and LED systems. Smart energy meters (DIN rail type) with built-in relays were installed to measure real-time power consumption (voltage, current, frequency, and energy usage) of the AC and LED units, enabling programmable on/off control. Internal environmental data were collected using a high-performance, industrial-grade temperature and humidity sensor. For control and processing tasks, an industrial-grade remote terminal unit (RTU) gateway was used. All devices were installed at strategic locations within the plant factory to ensure accurate data collection and operational control.

### 2.3. Dashboard and User Interface Development

A web-based dashboard interface was created using PHP Laravel, providing real-time visualization of energy consumption, environmental trends, and the status of AC and LED operations. The dashboard also included a user interface for manual control, scheduling, and threshold setting. Historical data analytics features were implemented to allow users to assess energy efficiency over time.

### 2.4. Control Logic and Automation Strategy

Three control strategies were developed and tested: (1) manual control via dashboard interface, (2) daily and weekly operational based on a specific schedule, and (3) Smart control using threshold triggers from sensor readings (e.g., activating AC when temperature exceeds 28°C). These strategies were embedded in the controller firmware, with logic parameters configurable via the user interface.

### 2.5. System Testing and Validation

Two experimental conditions were tested to evaluate the effect of varying AC settings on power consumption. In fixed condition, the AC unit would have operate continuously from 7:00 AM to 7:00 PM at a fixed temperature of 26 °C. Sensor-based condition introduced a smart control system, where the AC functioned based on real-time sensor data. In this setup, the AC would automatically switch on when the ambient temperature reaches 30 °C and turns off when the temperature reaches 24 °C.

## 3. Results and Discussion

### 3.1. System Component

The monitoring and control system integrates environmental sensors, energy monitoring, and cloud-based data storage. A temperature and moisture sensor collects environmental data and sends it via LoRa communication to a central Remote Terminal Unit (RTU) equipped with an energy meter sensor.

The RTU monitors electrical loads, including two single-phase air conditioners and two LED lights, providing insights into both environmental conditions and energy usage within the system.

The RTU then transmits the collected data through GSM communication to a cloud database, enabling remote monitoring and data analysis. By combining environmental sensing, energy measurement, and cloud connectivity, this system supports smarter decision-making, optimised energy consumption, and better environmental control for plant factory applications.

Figure 2 and Table 1 show all the hardware components used in the system.

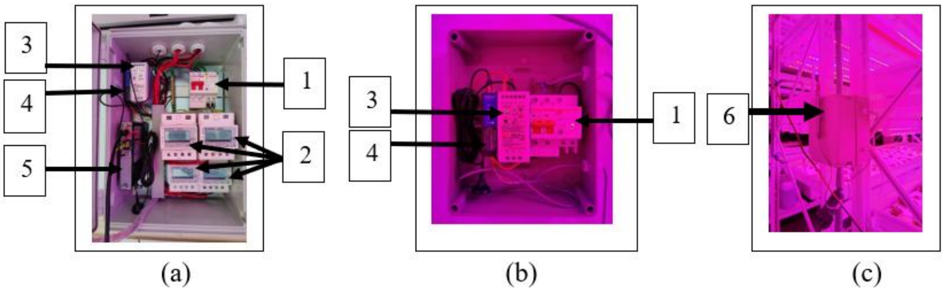


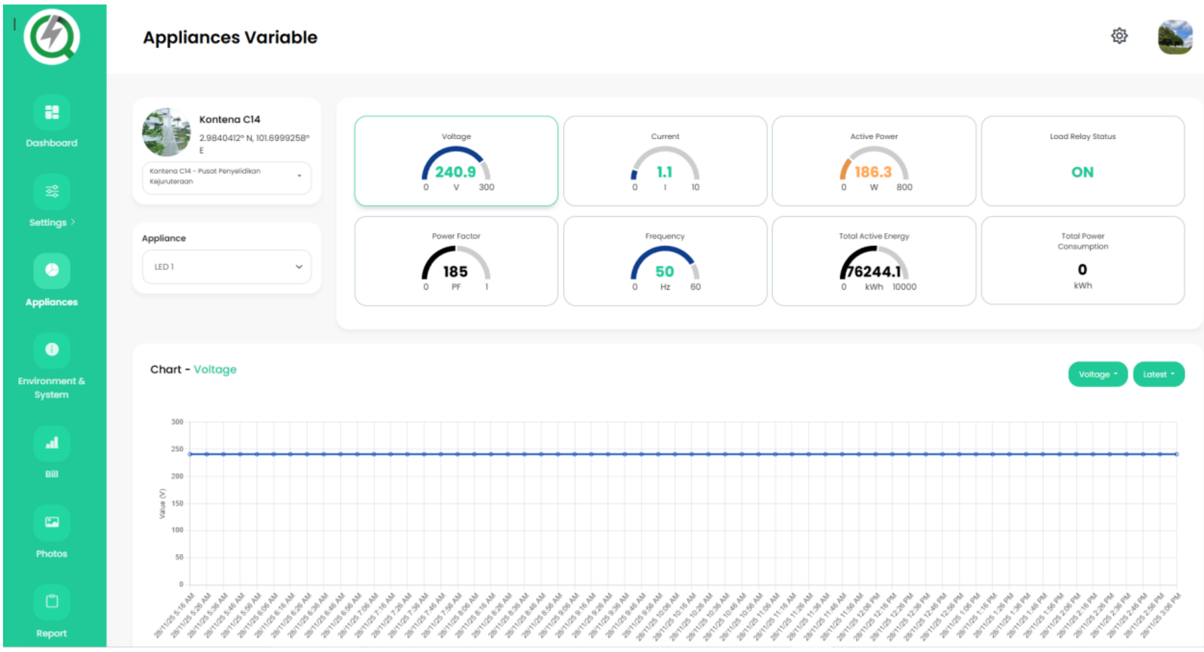

**Figure 2.** Hardware components used in the system (a) outside the planting area, (b) and (c) inside the planting area.

**Table 1.** Components used in the system.

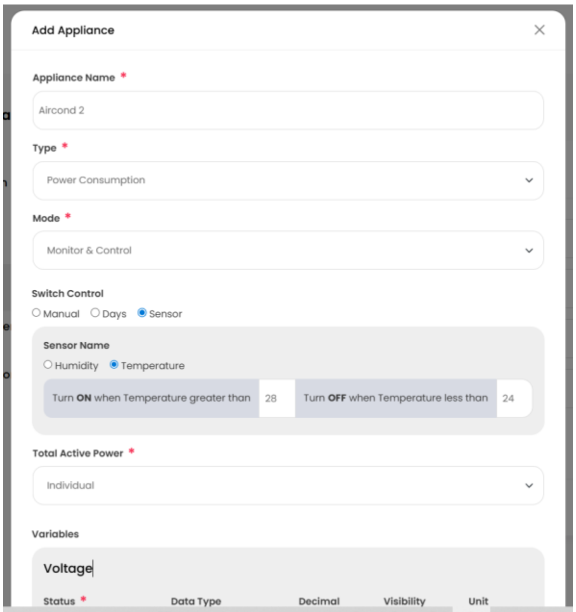
| No | Item | Quantity |
|---|---|---|
| 1 | Taixi RCCB + RCBO + MCB + SPD 4-in-1 Protection 20A | 2 |
| 2 | Eastron SDM320C Power Meter Sensor with Relay Control (Single SDM) | 4 |
| 3 | MeanWell 24V 2.5A Power Supply | 2 |
| 4 | Amsamotion Lora-RS485 Wireless Data Transmission | 2 |
| 5 | Tbox TG2 Industrial Remote Terminal Unit | 1 |
| 6 | Asair Temperature & Humidity RS485 Sensor | 1 |

## 3.2. User Interface and Operational Usability

The web-based dashboard developed using PHP Laravel enabled real-time visualisation and control of system parameters. User Acceptance Test (UAT) was conducted with the participation of 15 end-users, representing researchers involved in plant factory development. 20 test cases were executed, covering critical workflows such as user login, sensor data upload, sensor data update, control mechanism, report generation, and data export. Of these, 18 test cases were successfully passed, while 2 revealed issues related to data visualisation in the graph. These issues were documented and subsequently addressed by the development team, after which retesting confirmed successful resolution. Based on the high completion rate and user satisfaction feedback, the UAT concluded with formal sign-off, confirming that the system met the initial requirements and was deemed ready for deployment in the actual environment.




(a)




(b)

**Figure 3.** Screenshot of Real-Time Dashboard Interface includes a screenshot showing (a) live energy usage, and (b) AC control settings.

The system's function includes the ability to monitor and control energy usage. The monitoring function enables real-time monitoring of electrical energy usage (Figure 3a), as well as temperature and humidity readings inside the plant factory. While in the control function (Figure 3b), the system allows users to control AC and LED operations. The AC operation can be controlled in three modes: manually on and off, according to a schedule, and based on temperature sensor readings. For the LED operation, it can be controlled manually or according to a schedule.

### 3.3. Functional test of the system

To evaluate the efficiency of different control methods, daily energy consumption data were collected over 19 days under two AC control modes: fixed and sensor-based control using the newly developed system (see Figure 4). For the manual setting, the AC is set to on at 26 °C. For smart control, the AC is set to on when the temperature data reaches 30 °C and off when the temperature data reaches 24 °C.

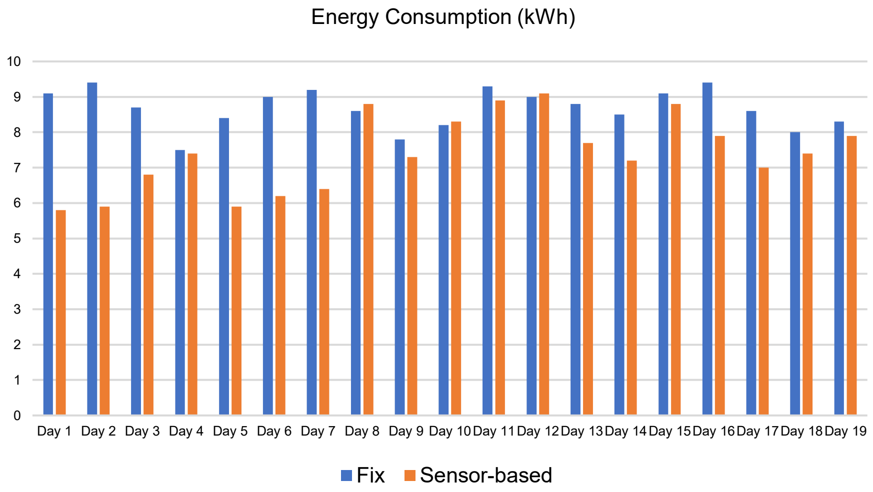



**Figure 4.** Daily energy consumption under different control strategies.

The energy consumption data for both the Fix and Sensor-based systems were analysed to understand their central tendency, variability, and confidence intervals. The mean energy consumption for the Fix system was found to be 8.68 kWh, while the Sensor-based system recorded a lower mean of 7.41 kWh, indicating that the Fix system generally consumed more energy. In terms of variance, the Fix system exhibited lower variability (0.30 kWh) compared to the Sensor-based system (1.14 kWh), suggesting greater fluctuation in energy usage for the Sensor-based approach across the 19-day period. The 95% confidence intervals further support these observations: the Fix system ranged between 8.42 kWh and 8.94 kWh, whereas the Sensor-based system ranged between 6.89 kWh and 7.92 kWh. These results indicate a high level of confidence in the mean values obtained and reinforce that, although both systems follow similar daily patterns, the Fix system consistently consumes more energy with less variation, while the Sensor-based system experiences more fluctuation but remains more energy-efficient overall.

Beyond performance comparison, the development of the energy monitoring system also aligns with national sustainability initiatives, particularly the Energy Efficiency and Conservation Act (EECA) 2024. The EECA emphasises improved energy efficiency and sustainable practices across all industries, including agriculture. By providing real-time monitoring of energy consumption, the proposed system enables plant factories to identify inefficiencies, optimise energy use, and comply with the energy performance requirements stipulated under the EECA. Furthermore, the system supports ongoing energy audits mandated by the Act, ensuring continuous optimisation of energy consumption in line with national conservation targets. In this regard, the system contributes not only to operational improvements but also to broader efforts aimed at reducing energy waste and promoting sustainability within the agricultural sector.

From an economic perspective, the system demonstrates strong financial viability. Assuming a small container-type plant factory with four monitored subsystems (such as two AC units and two lighting rows) and using low-cost IoT-based energy meters and a Modbus-to-LoRa gateway, the estimated total upfront cost (CAPEX) for the system is approximately RM 1,200. Based on the observed daily energy savings of about 1.27 kWh and using a typical electricity tariff of RM 0.60 per kWh, the annual cost savings amount to roughly RM 278. Under this baseline scenario, the simple payback period is approximately 4.3 years. Over a projected system lifespan of 10 years, excluding major maintenance, the return on investment (ROI) is estimated at 131%. Sensitivity analysis further indicates that even under lower tariff rates or slightly reduced energy savings, the payback period remains within 5 to 6 years, reinforcing the economic attractiveness of the proposed solution for small to medium-scale container-type plant factories.

In addition to its energy-saving and economic benefits, the system is designed with strong reliability, maintainability, and security considerations. Redundancy in key components, such as sensors and communication modules, enhances the system's Mean Time Between Failures (MTBF), thereby reducing downtime. Automated fault diagnosis and real-time alert mechanisms allow early detection of anomalies and support timely corrective actions, ensuring continuous system operation with minimal manual intervention. For disaster recovery, cloud-based backups and fail-over mechanisms protect data integrity and maintain system availability during hardware failures or network interruptions. Data security is prioritised through end-to-end encryption, role-based access control, and adherence to industry-standard system hardening practices, including routine updates and security patches. Collectively, these measures ensure that the monitoring system remains resilient, secure, and reliable for long-term deployment in real-world agricultural environments.

## 4. Conclusion

This study demonstrates that integrating IoT-enabled smart energy monitoring and control systems in plant factories enhances energy efficiency while maintaining optimal growing conditions. The sensor-based system outperformed the fixed control strategy, reducing energy consumption by approximately 1.27 kWh/day without compromising thermal comfort, making it suitable for large-scale agricultural use. The system's web-based dashboard and real-time monitoring features provide operational transparency, enabling stakeholders to make informed, data-driven decisions. Moreover, the economic analysis shows that the system is financially viable, with a simple payback period of 4.3 years and an ROI of 131% over 10 years. Successful user acceptance testing further confirms the system's readiness for practical adoption. Beyond energy savings, the system contributes to sustainability objectives by reducing carbon footprints, aligning with the Energy Efficiency and Conservation Act (EECA) 2024, and promoting environmentally responsible practices. In addition, its robust reliability, fault diagnosis, and security features contribute to long-term operational stability. Future research should focus on integrating renewable energy sources, predictive analytics, and enhancing system intelligence and adaptability to optimise energy management further.

## Declaration of Conflict of Interest

The authors declared no conflicts of interest with any other party on the publication of the current work.

## References

[1] F. Shrouf, J. Ordieres, and G. Miragliotta, Smart factories in Industry 4.0: A Review of the Concept and of Energy Management Approached in Production based on the Internet of Things Paradigm, in: 2014 IEEE International Conference on Industrial Engineering and Engineering Management, IEEE, 2014: pp. 697–701. https://doi.org/10.1109/ieem.2014.7058728.

[2] P. Pawar, and P. Vittal K, Design and Development of Advanced Smart Energy Management System Integrated with IoT Framework in Smart Grid Environment. Journal of Energy Storage 25 (2019) 100846. https://doi.org/10.1016/j.est.2019.100846.

[3] J.C. Kabugo, S.-L. Jämsä-Jounela, R. Schiemann, and C. Binder, Industry 4.0 Based Process Data Analytics Platform: A Waste-to-Energy Plant Case Study. International Journal of Electrical Power & Energy Systems 115 (2020) 105508. https://doi.org/10.1016/j.ijepes.2019.105508.

[4] L. Tang, and Y. Meng, Data Analytics and Optimization for Smart Industry. Frontiers of Engineering Management 8 (2021) 157–171. https://doi.org/10.1007/s42524-020-0126-0.

[5] M. Wei, S.H. Hong, and M. Alam, An IoT-Based Energy-Management Platform for Industrial Facilities. Applied Energy 164 (2016) 607–619. https://doi.org/10.1016/j.apenergy.2015.11.107.

[6] Y. Wu, H.-N. Dai, H. Wang, Z. Xiong, and S. Guo, A Survey of Intelligent Network Slicing Management for Industrial IoT: Integrated Approaches for Smart Transportation, Smart Energy, and Smart Factory. IEEE Communications Surveys & Tutorials 24 (2022) 1175–1211. https://doi.org/10.1109/comst.2022.3158270.

[7] J. Wan, B. Chen, S. Wang, M. Xia, D. Li, and C. Liu, Fog Computing for Energy-Aware Load Balancing and Scheduling in Smart Factory. IEEE Transactions on Industrial Informatics 14 (2018) 4548–4556. https://doi.org/10.1109/tii.2018.2818932.

[8] S.K. Rathor, and D. Saxena, Energy Management System for Smart Grid: An Overview and Key Issues. International Journal of Energy Research 44 (2020) 4067–4109. https://doi.org/10.1002/er.4883.

[9] H. Shahinzadeh, J. Moradi, G.B. Gharehpetian, H. Nafisi, and M. Abedi, Internet of Energy (IoE) in Smart Power Systems, in: 2019 5th Conference on Knowledge Based Engineering and Innovation (KBEI), IEEE, 2019. https://doi.org/10.1109/kbei.2019.8735086.

[10] N. Mohamed, J. Al-Jaroodi, and S. Lazarova-Molnar, Leveraging the Capabilities of Industry 4.0 for Improving Energy Efficiency in Smart Factories. IEEE Access: Practical Innovations, Open Solutions 7 (2019) 1–1. https://doi.org/10.1109/access.2019.2897045.

[11] V. Kumar, K.V. Sharma, N. Kedam, A. Patel, T.R. Kate, and U. Rathnayake, A Comprehensive Review on Smart and Sustainable Agriculture Using IoT Technologies. Smart Agricultural Technology 8 (2024) 100487. https://doi.org/10.1016/j.atech.2024.100487.