

Advancing Energy-Efficient Technologies in the Internet of Things (IoT): A Comprehensive Analysis

Roberto Kaban^{1)*}

¹⁾Institut Teknologi dan Bisnis Indonesia, Indonesia
¹⁾roberto.kaban@yahoo.com

Submitted : 26 February 2025 | **Accepted** : 11 March 2025 | **Published** : 25 March 2025

Abstract: In the era of the Internet of Things (IoT), energy efficiency has become one of the primary research focuses. This study explores five Scopus-indexed papers in the Q1 and Q2 categories, published between 2022 and 2024. The selected papers discuss various strategies to enhance energy efficiency in the IoT context. This review provides a comprehensive overview of the latest efforts in delivering energy-efficient solutions to support the growth and sustainability of IoT. Resource optimization, both in wireless communication infrastructure and data management, is a crucial step in fostering an environmentally friendly IoT ecosystem. Through innovative approaches and intelligent resource optimization, IoT has significant potential to become more energy-efficient and contribute to global environmental sustainability goals.

Keywords: Internet of Things (IoT), energy efficiency, low-cost sensors, resource allocation algorithms

INTRODUCTION

The Internet of Things (IoT) is a paradigm regarded as a promising effort to extend communication from human-to-human to human-to-device and device-to-device interactions (Alsoufi et al., 2021). IoT has become integral to daily life, connecting various devices—from vehicles to household appliances—to provide more efficient and interconnected services (Moutaib et al., 2021). With the increasing number of interconnected devices, the demand for reliable and efficient infrastructure has become more urgent (Al-Mutawa & Albourae, 2020). This technology offers numerous benefits, including enhanced productivity, process automation, and resource optimization across various sectors such as industry, healthcare, transportation, and households.

Alongside the rapid growth of IoT, a significant challenge arises in terms of energy consumption (Macedo et al., 2019; Sebestyen et al., 2025). IoT devices generally have power limitations, particularly those relying on battery-powered sources with limited capacity (Geetha & Gouthami, 2016). Moreover, the high energy consumption of IoT communication and computing networks can lead to increased operational costs and significant environmental impacts (Aldin et al., 2024). Therefore, energy efficiency has become a crucial aspect in developing IoT infrastructure to ensure the long-term sustainability of these systems.

Research on energy-efficient computing is gaining increasing attention due to the urgency of finding solutions that enable IoT networks to operate with lower power consumption without compromising performance and reliability (Aldin et al., 2024; Wu et al., 2022). Various approaches have been developed, including resource optimization algorithms, the utilization of renewable energy sources such as photovoltaic (PV) systems, and the advancement of low-power wireless communication technologies like LoRa/LoRaWAN (Abdul-Qawy et al., 2020). Additionally, the adoption of intelligent technologies such as machine learning and intelligent reflecting surfaces (IRS) has the potential to enhance energy efficiency in IoT communication and data management systems (Ogbebor et al., 2020).

With growing awareness of the environmental impact of high energy consumption, there is a stronger push to adopt sustainable solutions in technology infrastructure development (Aldin et al., 2024; O'Dwyer et al., 2020). A comprehensive study on energy efficiency in the IoT context is not only essential to understanding existing challenges but also to identifying innovative opportunities that can help address these issues. By examining the background and emerging trends in energy-efficient computing, researchers and practitioners can develop more effective solutions that can be implemented in both existing and future IoT networks (O'Dwyer et al., 2020).

*Roberto Kaban



This study aims to provide insights into approaches and technologies that can enable more energy-efficient and sustainable IoT networks. By reviewing various energy optimization strategies in IoT, including the application of low-cost sensors, low-power communication, efficient resource allocation, and data deduplication techniques, this research seeks to identify innovative solutions that can enhance the efficiency and sustainability of IoT systems in the future.

LITERATURE REVIEW

The paper Low-Cost Sensors for Indoor PV Energy Harvesting Estimation Based on Machine Learning (Politi et al., 2022) aims to address the issue of estimating indoor photovoltaic (PV) energy harvesting using low-cost sensors. The background of this research is the need for accurate estimation to improve energy utilization efficiency. The proposed method involves applying machine learning techniques to estimate PV energy harvesting based on data collected from sensors installed indoors. The research includes implementing machine learning techniques and conducting experiments using datasets obtained from these sensors. The results demonstrate that the proposed method can provide accurate estimations at a lower cost. The conclusion is that using low-cost sensors and machine learning techniques can be an effective solution for estimating indoor PV energy harvesting.

The paper A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems (Milarokostas et al., n.d.) provides a comprehensive study of Low Power Wide Area Networks (LPWANs), focusing on the potential of LoRa/LoRaWAN systems. The background of this research is the growing interest in LPWANs as a communication infrastructure suitable for IoT applications requiring long-range communication and low power consumption. The proposed method involves an in-depth analysis of the characteristics, advantages, and disadvantages of LPWANs, with a particular emphasis on LoRa/LoRaWAN technology. The study is conducted through literature reviews, comparative analyses, and evaluations of the performance and potential implementation of LoRa/LoRaWAN systems. The results indicate that LoRa/LoRaWAN has significant potential for various IoT applications that require efficient and energy-saving communication networks. The conclusion is that LPWANs, especially LoRa/LoRaWAN systems, are promising solutions to support the growing IoT ecosystem.

The paper Energy Efficient Resource Allocation for Wireless Powered UAV Wireless Communication System with Short Packet (Xie et al., 2023) discusses energy-efficient resource allocation for a wireless communication system powered by unmanned aerial vehicles (UAVs) with short-packet transmission. The background of this research is the increasing interest in using UAVs to support wireless communication, particularly in IoT contexts that require low-power devices and efficient data transmission. The proposed method involves developing a resource allocation algorithm that considers the unique characteristics of UAV communication, including energy efficiency and data transmission requirements in short-packet form. The research is conducted through mathematical modeling, simulations, and performance analysis of the proposed algorithm. The results show that the proposed approach improves energy efficiency and overall communication performance in UAV-powered wireless communication systems with short-packet transmission. The conclusion is that developing an efficient resource allocation algorithm can enhance UAV-based wireless communication systems to support IoT applications requiring fast and energy-efficient data transmission.

The paper Energy-Efficient Device-to-Device Communications for Green Internet of Things Using Unmanned Aerial Vehicle-Mounted Intelligent Reflecting Surface (Tan et al., 2024) explores energy-efficient device-to-device (D2D) communication for a green IoT using an intelligent reflecting surface (IRS) mounted on an unmanned aerial vehicle (UAV). The background of this study is the need for energy-efficient communication solutions to support IoT growth while addressing challenges related to power consumption and reliable connectivity. The proposed method includes deploying IRS on UAVs to enhance signal quality and energy efficiency in D2D communication within IoT contexts. The research is conducted through mathematical modeling, computer simulations, and system performance analysis. The results indicate that this approach can improve energy efficiency and communication quality in IoT environments. The conclusion is that UAV-mounted IRS has great potential to support the development of a green IoT by providing energy-efficient D2D communication.

The paper Energy-Efficient De-Duplication Mechanism for Healthcare Data Aggregation in IoT (Khan et al., 2024) discusses an energy-efficient deduplication mechanism for healthcare data aggregation in IoT. The background of this research is the need for efficient and secure data management in the increasingly interconnected healthcare sector through IoT. The proposed method involves developing a deduplication mechanism that can efficiently identify and remove duplicate data, thereby reducing unnecessary energy consumption in data aggregation processes. The research is conducted through deduplication algorithm modeling, computer simulations, and performance evaluation of the proposed mechanism. The results demonstrate that this approach can reduce energy consumption for managing healthcare data in IoT environments. The conclusion is that an

efficient deduplication mechanism can help improve energy efficiency and data management in IoT-connected healthcare services.

METHOD

The research methodology employed in this study involves collecting papers from reputable journals indexed in Scopus, specifically within the Q1 and Q2 categories, and published between 2022 and 2024. The selection process focuses on identifying five papers that are most relevant to the topic of Low-Energy IoT. These papers are carefully chosen based on their quality and the significance of their contributions to the field. The primary criteria for selection include their focus on low energy consumption, advancements in energy harvesting technologies, resource optimization, and power management strategies within IoT systems.

To ensure the relevance and credibility of the selected papers, the study follows a systematic approach that involves reviewing abstracts, methodologies, and key findings to assess their alignment with the research objectives. Papers that present innovative solutions, novel frameworks, or significant improvements in energy-efficient IoT applications are given priority. By narrowing the selection to high-impact publications, this research aims to provide a comprehensive analysis of the latest advancements in Low-Energy IoT, offering valuable insights into emerging trends, challenges, and potential future directions in this field.

RESULT

The comparison between papers based on methods, focus, and results is presented in Table I below.

TABLE I. COMPARISON OF PAPERS

Paper	Method	Focus	Results
Low-Cost Sensors for Indoor PV Energy Harvesting Estimation Based on Machine Learning(Politi et al., 2022)	Utilizes machine learning techniques for PV energy estimation.	Estimation of indoor photovoltaic energy harvesting.	Provides accurate energy estimation at a low cost.
A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems(Milarokostas et al., n.d.)	In-depth analysis of the characteristics and potential of LoRa/LoRaWAN systems.	Comprehensive study on LPWAN networks.	LoRa/LoRaWAN has significant potential for IoT applications requiring long-range communication and low power consumption.
Energy Efficient Resource Allocation for Wireless Powered UAV Wireless Communication System(Xie et al., 2023)	Development of a resource allocation algorithm for UAV communication.	Resource allocation in UAV-based wireless communication.	Improves energy efficiency and communication performance.
Energy-Efficient Device-to-Device Communications for Green Internet of Things Using UAV-Mounted IRS(Tan et al., 2024)	Implementation of Intelligent Reflecting Surface (IRS) on UAVs.	Device-to-device communication in IoT.	Enhances energy efficiency and communication quality in IoT environments.
Energy-Efficient De-Duplication Mechanism for Healthcare Data Aggregation in IoT(Khan et al., 2024)	Development of a de-duplication mechanism for healthcare data aggregation.	Healthcare data management in IoT.	Reduces energy consumption for healthcare data management.

The paper “Low-Cost Sensors for Indoor PV Energy Harvesting Estimation Based on Machine Learning” not only reduces sensor costs but also enhances the accuracy of photovoltaic (PV) energy harvesting estimation indoors. By utilizing machine learning techniques, this study enables low-cost sensors to provide more precise estimates of the energy generated from indoor solar sources. This is crucial in the context of IoT, as it supports more efficient energy use, allowing IoT applications that rely on solar energy to operate more effectively and sustainably.

The paper "A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems" offers an in-depth understanding of LPWANs, particularly LoRa/LoRaWAN, which are well-known for their low power consumption. By focusing on the potential of LoRa/LoRaWAN systems, this study highlights how this technology can contribute to greater energy efficiency in long-range communication within IoT. This represents a significant step toward developing a more energy-efficient and environmentally friendly communication infrastructure for IoT applications.

The paper "Energy Efficient Resource Allocation for Wireless Powered UAV Wireless Communication System" develops an optimized resource allocation algorithm for UAV wireless communication. Considering the power constraints of wirelessly powered UAVs, this research aims to improve energy efficiency in UAV communication infrastructures within IoT. By optimizing resource utilization, the study contributes to the

development of energy-efficient communication systems that support IoT applications requiring high mobility and reliable wireless connectivity.

The paper "Energy-Efficient Device-to-Device Communications for Green Internet of Things Using UAV-Mounted IRS" highlights the application of Intelligent Reflecting Surface (IRS) on UAVs as a solution to enhance energy efficiency and communication quality in IoT environments. By leveraging IRS to improve signal quality in device-to-device communication, this study seeks to reduce unnecessary energy consumption and improve energy efficiency in IoT communication infrastructures.

The paper "Energy-Efficient De-Duplication Mechanism for Healthcare Data Aggregation in IoT" focuses on the development of a deduplication mechanism for managing healthcare data in IoT applications. By efficiently eliminating duplicate data, this research helps reduce the energy burden associated with healthcare data management, enabling IoT systems to operate more efficiently and economically in terms of energy consumption.

DISCUSSIONS

In the era of the Internet of Things (IoT), energy efficiency has become a crucial aspect of communication infrastructure development and resource management. Recent studies have proposed advanced technology-based solutions to optimize energy consumption across various IoT aspects, such as energy harvesting, wireless communication, and data management. This discussion outlines innovative approaches proposed in five related studies.

1. Indoor Photovoltaic Energy Harvesting Estimation

The study "Low-Cost Sensors for Indoor PV Energy Harvesting Estimation Based on Machine Learning" highlights the use of low-cost sensors to enhance the accuracy of indoor photovoltaic (PV) energy harvesting estimation. By leveraging machine learning techniques, this research enables IoT devices utilizing solar energy to operate more efficiently. Improved energy estimation accuracy is essential for effective energy resource management, particularly for IoT applications that rely on solar power in enclosed environments.

2. Energy Efficiency in LPWAN with LoRa/LoRaWAN

The paper "A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems" explores the potential of LoRa/LoRaWAN in improving IoT communication efficiency. Low Power Wide Area Networks (LPWAN) are known for their low power consumption, allowing for reduced energy requirements in long-range communication. By understanding the characteristics and advantages of LoRa/LoRaWAN, this research contributes to the development of a more energy-efficient and sustainable IoT communication infrastructure.

3. Optimized Resource Allocation for Wireless-Powered UAVs

In the context of wireless communication using Unmanned Aerial Vehicles (UAVs), the study "Energy Efficient Resource Allocation for Wireless Powered UAV Wireless Communication System" develops an optimized resource allocation algorithm. Considering the power limitations of wirelessly powered UAVs, this research aims to improve energy efficiency in UAV communication systems. This solution enables better resource management, supporting IoT applications that require high mobility and reliable connectivity.

4. Device-to-Device Communication Using UAV-Mounted IRS

The paper "Energy-Efficient Device-to-Device Communications for Green Internet of Things Using UAV-Mounted IRS" proposes the use of Intelligent Reflecting Surface (IRS) on UAVs to enhance device-to-device communication efficiency. With IRS, signal quality in IoT networks can be improved without a significant increase in power consumption. This allows for more stable and energy-efficient communication within IoT infrastructure, especially in scenarios involving mobile devices such as UAVs.

5. Data Deduplication Mechanism for Healthcare in IoT

Efficient data management in IoT applications is also essential, as proposed in "Energy-Efficient De-Duplication Mechanism for Healthcare Data Aggregation in IoT". The deduplication mechanism aims to reduce duplicate data in IoT-based healthcare systems, thereby saving energy in the data management process. Consequently, IoT systems can operate more efficiently in handling large-scale data, particularly in medical applications that require accuracy and rapid response.

The five studies discussed in this journal provide in-depth insights into efforts to enhance energy efficiency within the IoT ecosystem. From PV energy harvesting estimation and LPWAN communication optimization to

UAV resource allocation and healthcare data deduplication, each study presents an innovative solution to address IoT power consumption challenges. The implications of these studies are crucial in supporting the development of more sustainable and energy-efficient IoT technologies in the future.

CONCLUSION

Through the analysis of these five papers, a comprehensive overview of efforts to enhance energy efficiency in IoT technology has been identified. From the use of low-cost sensors and machine learning techniques for indoor photovoltaic energy estimation to the implementation of advanced technologies such as Intelligent Reflecting Surface (IRS) on Unmanned Aerial Vehicles (UAVs), each paper explores various approaches to achieving energy efficiency. Resource optimization, both in wireless communication infrastructure and data management, is a crucial step in supporting an eco-friendly IoT ecosystem.

With the adoption of appropriate technologies, intelligent resource management, and increased awareness of innovative solutions, IoT can become more energy-efficient and contribute to global environmental sustainability goals. By continuously innovating and adopting eco-friendly solutions, IoT holds great potential as a key driver in supporting the transition toward a more sustainable future.

REFERENCES

- Abdul-Qawy, A. S. H., S. Almurisi, N. M., & Tadisetty, S. (2020). Classification of Energy Saving Techniques for IoT-based Heterogeneous Wireless Nodes. *Procedia Computer Science*, 171, 2590–2599. <https://doi.org/10.1016/j.procs.2020.04.281>
- Aldin, H. N. S., Ghods, M. R., Nayebipour, F., & Torshiz, M. N. (2024). A comprehensive review of energy harvesting and routing strategies for IoT sensors sustainability and communication technology. *Sensors International*, 5, 100258. <https://doi.org/10.1016/j.sintl.2023.100258>
- Al-Mutawa, R. F., & Albouraey, F. (2020). A Smart Home System based on Internet of Things. *International Journal of Advanced Computer Science and Applications*, 11(2). <https://doi.org/10.14569/IJACSA.2020.0110234>
- Alsoufi, M. A., Razak, S., Siraj, M. M., Nafea, I., Ghaleb, F. A., Saeed, F., & Nasser, M. (2021). Anomaly-Based Intrusion Detection Systems in IoT Using Deep Learning: A Systematic Literature Review. *Applied Sciences*, 11(18), 8383. <https://doi.org/10.3390/app11188383>
- Geetha, S., & Gouthami, S. (2016). Internet of things enabled real time water quality monitoring system. *Smart Water*, 2(1), 1. <https://doi.org/10.1186/s40713-017-0005-y>
- Khan, M. N. U., Cao, W., Tang, Z., Ullah, A., & Pan, W. (2024). Energy-Efficient De-Duplication Mechanism for Healthcare Data Aggregation in IoT. *Future Internet*, 16(2), 66. <https://doi.org/10.3390/fi16020066>
- Macedo, E. L. C., De Oliveira, E. A. R., Silva, F. H., Mello, R. R., Franca, F. M. G., Delicato, F. C., De Rezende, J. F., & De Moraes, L. F. M. (2019). On the security aspects of Internet of Things: A systematic literature review. *Journal of Communications and Networks*, 21(5), 444–457. <https://doi.org/10.1109/JCN.2019.000048>
- Milarokostas, C., Tsolkas, D., Passas, N., & Merakos, L. (n.d.). *A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems*.
- Moutaib, M., Ahajjam, T., Fattah, M., Farhaoui, Y., Aghoutane, B., & El Bekkali, M. (2021). Optimization of the Energy Consumption of Connected Objects. *International Journal of Interactive Mobile Technologies (iJIM)*, 15(24), 176–190. <https://doi.org/10.3991/ijim.v15i24.26985>
- O'Dwyer, E., Pan, I., Charlesworth, R., Butler, S., & Shah, N. (2020). Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems. *Sustainable Cities and Society*, 62, 102412. <https://doi.org/10.1016/j.scs.2020.102412>
- Ogbebor, J. O., Imoize, A. L., & Atayero, A. A.-A. (2020). Energy Efficient Design Techniques in Next-Generation Wireless Communication Networks: Emerging Trends and Future Directions. *Wireless Communications and Mobile Computing*, 2020, 1–19. <https://doi.org/10.1155/2020/7235362>
- Politi, B., Foucaran, A., & Camara, N. (2022). Low-Cost Sensors for Indoor PV Energy Harvesting Estimation Based on Machine Learning. *Energies*, 15(3), 1144. <https://doi.org/10.3390/en15031144>
- Sebestyen, H., Popescu, D. E., & Zmaranda, R. D. (2025). A Literature Review on Security in the Internet of Things: Identifying and Analysing Critical Categories. *Computers*, 14(2), 61. <https://doi.org/10.3390/computers14020061>
- Tan, F., Pang, S., Cao, Y., Chen, H., & Lv, T. (2024). Energy-Efficient Device-to-Device Communications for Green Internet of Things Using Unmanned Aerial Vehicle-Mounted Intelligent Reflecting Surface. *Drones*, 8(4), 122. <https://doi.org/10.3390/drones8040122>

-
- Wu, Y., Lu, P., Bu, X., Liu, S., Zhong, C., & Liu, C. (2022). Computing offloading method with low power consumption constraint for smart grid. *Journal of Physics: Conference Series*, 2215(1), 012010. <https://doi.org/10.1088/1742-6596/2215/1/012010>
- Xie, J., Chang, Z., Guo, X., & Hamalainen, T. (2023). Energy Efficient Resource Allocation for Wireless Powered UAV Wireless Communication System With Short Packet. *IEEE Transactions on Green Communications and Networking*, 7(1), 101–113. <https://doi.org/10.1109/TGCN.2022.3218314>