



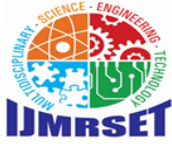
International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 9, Issue 4, April 2026



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

Carbon-Aware Federated RL for Smart Building Energy Optimization

M. Mohammed Jalaluddin¹, Naresh S D²

Assistant Professor, Department of Computer Applications, B.S Abdur Rahman Crescent Institute of Science and
Technology, Tamil Nadu, India¹

MCA 2nd Year Department of Computer Applications, B.S Abdur Rahman Crescent Institute of Science and Technology,
Tamil Nadu, India²

ABSTRACT- Buildings account for a substantial share of global electricity consumption and carbon emissions, particularly in rapidly urbanizing regions such as India. Conventional building energy management systems rely on static rule-based strategies that fail to adapt to dynamic occupancy patterns, fluctuating electricity tariffs, and real-time grid carbon intensity. To address these limitations, this paper proposes a Carbon-Aware Federated Reinforcement Learning (CAFRL) framework for multi-objective energy optimization in smart buildings. The proposed framework integrates IoT-enabled sensors to collect real-time data on energy consumption, occupancy behavior, indoor environmental conditions, and renewable energy availability. A reinforcement learning agent is deployed at each building to optimize HVAC, lighting and appliance scheduling. Unlike traditional approaches, the reward function is dynamically adjusted based on real-time carbon intensity of the power grid, enabling carbon-constrained decision-making. To preserve data privacy and enhance scalability across multiple buildings, a federated learning architecture is adopted, allowing collaborative model training without sharing raw data. The system simultaneously minimizes energy cost and carbon emissions while maintaining occupant comfort within predefined thresholds. Additionally, a sustainability intelligence index is introduced to quantify long-term building performance toward net-zero energy targets. Simulation results demonstrate significant improvements in energy efficiency, carbon reduction and comfort stability compared to conventional rule-based and centralized learning approaches. The proposed framework offers a scalable, privacy-preserving and carbon-optimized solution for next-generation sustainable smart buildings.

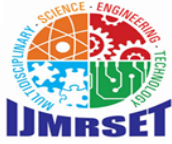
I. INTRODUCTION

In today's rapidly developing world, the demand for energy in modern buildings has increased significantly due to urbanization and technological growth. Buildings consume a large portion of electrical energy and play a major role in contributing to carbon emissions. This creates a serious need to manage energy efficiently, not only to reduce operational costs but also to minimize environmental impact. Hence, adopting smarter approaches to energy management has become essential for achieving sustainability in building operations.

Many of the existing energy management approaches in buildings rely on predefined rules or manual control methods. These approaches are not flexible enough to adapt to real-time changes such as varying occupancy, environmental conditions or fluctuations in electricity pricing. As a result, energy is often used inefficiently, leading to unnecessary wastage and increased costs. This limitation highlights the importance of developing a more adaptive and intelligent system for managing energy usage.

To address these challenges, this project introduces a Carbon-Aware Smart Energy Management System that makes use of IoT technology for real-time monitoring and control. The system gathers data from sensors such as temperature, humidity and occupancy to understand the current conditions within the building. In addition to this, it also incorporates external data like electricity tariff rates and carbon intensity through cloud or API services. This combination of internal and external data helps in making more informed and effective decisions.

The proposed system focuses on improving energy efficiency through intelligent decision-making while ensuring user comfort. It automatically regulates building devices such as HVAC systems, lighting and other appliances based on real-time data and user preferences. The system also provides alerts and reports, allowing users to track energy usage and



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

understand their carbon impact. Overall, this approach supports reduced energy consumption, lower costs and promotes environmentally responsible smart building management.

II. RELATED WORKS

Recent research in smart building energy management has focused on improving efficiency through the integration of IoT and intelligent algorithms. Several studies highlight the importance of real-time monitoring using sensor networks to collect data such as temperature, humidity and occupancy. These systems help in understanding building conditions and enable better control of energy usage. However, many of these approaches mainly focus on monitoring rather than intelligent optimization.

A number of research works have explored the use of machine learning techniques for predicting energy consumption and improving control strategies. Methods such as deep learning and reinforcement learning have been applied to optimize HVAC systems and reduce energy usage. These models learn from historical data and adjust system behavior accordingly. While they provide better performance compared to static approaches, most of them rely on centralized data processing, which may raise concerns related to scalability and data privacy.

Ekanayaka et al. (2025) conducted a comprehensive systematic review and meta-analysis of AI-based energy optimization techniques for smart buildings. The study evaluated 126 research articles and reported that reinforcement learning approaches achieved an average energy saving of approximately 22%. Despite strong benchmarking results, only a small percentage of the reviewed studies demonstrated real-world implementation, indicating limited scalability and deployment maturity.

Wei et al. (2024) proposed a Deep Q-Network (DQN)-based HVAC control strategy for smart buildings. Their approach enabled real-time adaptive temperature control and improved occupant comfort while reducing energy consumption. However, the study primarily focused on energy efficiency and did not incorporate grid carbon intensity or dynamic electricity tariffs into the reward function. Furthermore, the framework relied on centralized model training, raising potential data privacy concerns.

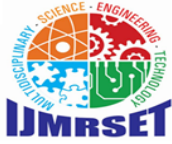
Zhang et al. (2024) introduced a Federated Learning-based energy management framework to enable privacy-preserving collaboration among multiple buildings. By sharing model parameters instead of raw data, the approach addressed data confidentiality issues. Nevertheless, the framework did not integrate carbon-aware optimization mechanisms and faced communication overhead challenges during model aggregation.

Ruelens et al. (2023) applied Multi-Agent Reinforcement Learning (MARL) for demand-side energy optimization in smart grids. Their distributed learning strategy effectively managed peak loads and improved grid stability. However, the training process was computationally complex and the study lacked explicit consideration of carbon emission reduction as an optimization objective.

Ahmad et al. (2023) developed an LSTM-based building energy load forecasting model to enhance prediction accuracy. While the model demonstrated strong forecasting performance, it focused solely on load prediction without integrating real-time control or optimization strategies for energy reduction and carbon mitigation. Furthermore, federated learning has emerged as a promising solution to address privacy issues in distributed energy management systems. Instead of sharing raw data, multiple buildings can collaboratively train models by sharing only model updates. This approach ensures data privacy while improving learning performance across different environments. Despite its advantages, combining federated learning with real-time energy optimization in smart buildings is still relatively unexplored, which forms the motivation for this project.

III. PROPOSED SYSTEM

The proposed system is a Carbon-Aware Smart Energy Management System designed to intelligently monitor, analyze, and optimize energy consumption in smart buildings. The primary objective of the system is to reduce energy wastage, minimize operational costs and lower carbon emissions while ensuring user comfort. Unlike basic energy management approaches, the proposed system operates dynamically by continuously adapting to real-time conditions and external factors.



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

The system is built using IoT technology, where multiple sensors are deployed within the building environment to collect real-time data. These sensors measure important parameters such as temperature, humidity, and occupancy, which play a crucial role in understanding the energy requirements of the building. The collected data is transmitted to the central system for further processing. In addition to internal sensor data, the system also integrates external information such as electricity tariff rates and carbon intensity through cloud or API services. This allows the system to consider both cost and environmental impact while making decisions.

Once the data is collected, it undergoes processing and analysis to extract meaningful insights. The system evaluates current conditions, user preferences and external factors to determine the most efficient way to manage energy usage. Based on this analysis, intelligent decision-making mechanisms are applied to identify optimal control actions. These decisions ensure that energy is utilized only when necessary, thereby avoiding unnecessary consumption and reducing carbon footprint.

The system then sends appropriate control signals to building devices such as HVAC systems, lighting systems and other electrical appliances. For example, the system can adjust temperature settings based on occupancy or switch off unused devices to save energy. This automated control not only improves efficiency but also reduces the need for manual intervention. At the same time, user comfort is maintained by considering predefined preferences and environmental conditions.

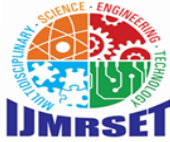
Furthermore, the proposed system provides continuous feedback to users in the form of alerts and detailed reports. These reports help users understand their energy consumption patterns and the associated carbon impact. This transparency enables better decision-making and encourages more sustainable behavior. The system is also designed to be scalable and adaptable, making it suitable for different types of buildings and usage scenarios.

ADVANTAGES

The proposed Carbon-Aware Smart Energy Management System significantly enhances energy efficiency by intelligently utilizing real-time data collected from IoT sensors. The system continuously monitors parameters such as temperature, humidity, and occupancy, and dynamically adjusts the operation of electrical devices like lighting and HVAC systems. This adaptive control mechanism ensures that energy is consumed only when necessary, thereby eliminating unnecessary wastage. As a result, the overall energy performance of the building is improved, making it more efficient and responsive to changing environmental conditions. Another key advantage of the system is its ability to reduce operational costs while maintaining user comfort. By integrating tariff data and optimizing energy usage during peak and off-peak hours, the system helps in minimizing electricity expenses. Additionally, automation reduces the need for constant manual monitoring and control, making the system more convenient and user-friendly. The inclusion of user preferences ensures that comfort is not compromised while achieving energy savings, thereby creating a balanced and efficient energy management environment.

The system also focuses on reducing carbon emissions by incorporating carbon intensity data into its decision-making process. This enables the system to operate in an environmentally responsible manner, contributing to sustainable development and greener building operations.

Furthermore, the system promotes environmental sustainability by incorporating carbon-aware decision-making. It considers carbon intensity data to schedule and control energy usage in a way that reduces overall carbon emissions. This contributes to eco-friendly building operations and supports global efforts toward reducing environmental impact. In addition, the system provides real-time reports and alerts, enabling users to track their energy consumption patterns and make informed decisions. This transparency not only improves awareness but also encourages responsible energy usage behavior.



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

IV. SYSTEM ARCHITECTURE

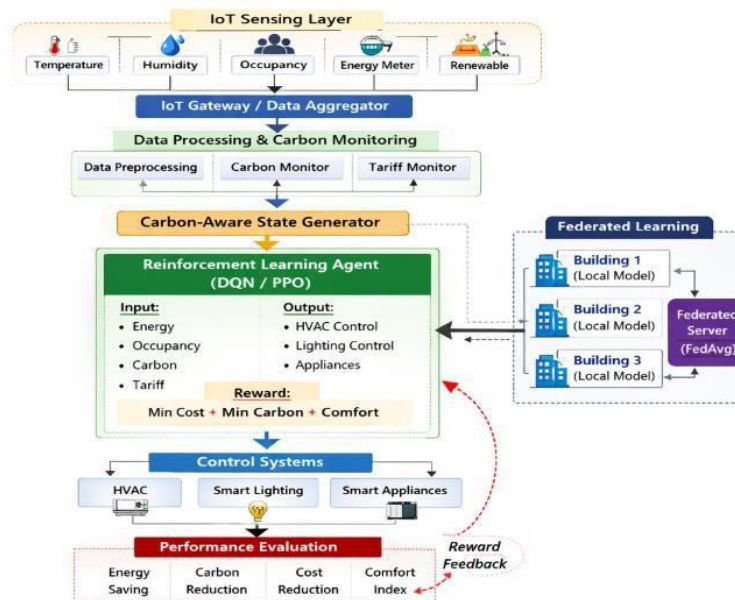


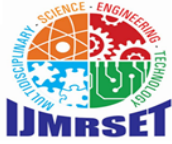
Fig (1) Architecture Diagram

Figure (1) presents the overall system architecture of the proposed Carbon-Aware Federated Reinforcement Learning framework designed for intelligent smart building energy optimization. The architecture integrates IoT-based sensing, real-time carbon monitoring, deep reinforcement learning and federated model aggregation into a unified decision-making framework. It is structured to enable adaptive, privacy-preserving and sustainability-driven control of building energy systems. The first layer comprises IoT sensors deployed within the building to continuously collect environmental and operational parameters such as indoor temperature, humidity, occupancy level, real-time energy consumption, and renewable energy availability. These heterogeneous sensor readings are transmitted to an IoT gateway, which performs data aggregation and synchronization before forwarding the structured data to the processing module. This layer ensures accurate and continuous monitoring of building conditions.

The data processing and carbon monitoring layer refines the collected data and enriches it with external information. Raw sensor inputs undergo preprocessing steps including normalization, filtering, and missing value handling. In parallel, real-time electricity tariff rates and grid carbon intensity values are retrieved from external sources. By integrating these parameters, a carbon-aware state representation is generated, enabling the system to incorporate economic and environmental considerations into the optimization process.

At the core of the framework, a Deep Reinforcement Learning agent, implemented using DQN or PPO, performs intelligent decision-making. Based on the carbon-aware state input, the agent determines optimal control actions such as HVAC setpoint adjustment, smart lighting control and appliance scheduling. A multi-objective reward function is designed to minimize electricity cost and carbon emissions while maintaining occupant comfort. Through iterative interaction and reward feedback, the agent learns an optimal control policy over time.

To enhance scalability and preserve data privacy, a Federated Learning mechanism is integrated into the architecture. Each participating building trains its local reinforcement learning model independently using local data. Instead of sharing raw data, only model parameters are transmitted to a central federated server, where they are aggregated using the Federated Averaging algorithm. The updated global model is then redistributed to all buildings. The optimized control signals are implemented in real time, and system performance is continuously evaluated using metrics such as energy savings, carbon reduction, cost efficiency, and comfort index, thereby forming a closed-loop sustainable optimization framework.



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

V. TECHNIQUES USED

A. Real-Time Sensing and Monitoring

The system uses IoT sensors to continuously collect real-time data such as temperature, humidity, and occupancy. This technique helps in understanding the current environmental conditions of the building and enables the system to respond instantly. It ensures that energy is used efficiently without unnecessary wastage.

B. Rule-Based Automation

The system follows predefined logical rules to control electrical devices. For example, lights and appliances are automatically turned off when no occupancy is detected. Similarly, devices are adjusted based on environmental conditions. This technique ensures quick, simple and reliable decision-making.

C. Carbon-Aware Energy Optimization

The system incorporates carbon intensity data to make environmentally responsible decisions. By considering carbon emissions along with energy consumption, the system reduces environmental impact and supports sustainable energy management.

D. API-Based Data Integration

The system integrates with cloud APIs to fetch real-time data such as electricity tariffs and carbon intensity. This allows the system to dynamically adapt to changing conditions and optimize energy usage based on cost and environmental factors.

E. Automated Control and Feedback

The system automatically sends control signals to building devices such as lights and HVAC systems. It also provides real-time alerts and reports to users, helping them monitor energy usage and make informed decisions.

VI. RESULT AND DISCUSSION

The proposed Carbon-Aware Smart Energy Management System was tested under different environmental and usage conditions to evaluate its performance. The system successfully collected real-time data from IoT sensors and responded effectively by controlling building devices such as lighting and HVAC systems. The automation based on occupancy and environmental parameters ensured that energy was utilized only when required, thereby reducing unnecessary power consumption.

The integration of carbon intensity and tariff data further improved the system's decision-making capability. The system was able to adjust energy usage based on cost and environmental impact, leading to optimized energy consumption. Compared to conventional systems, the proposed model demonstrated better efficiency in reducing electricity usage and operational cost while maintaining user comfort.

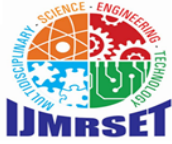
Additionally, the system provided real-time alerts and reports, allowing users to monitor their energy usage patterns. This improved user awareness and encouraged responsible energy consumption behavior. Overall, the system performed reliably, with minimal manual intervention and proved to be an effective solution for smart building energy management.

VII. CONCLUSION

The Carbon-Aware Smart Energy Management System presents an efficient and intelligent approach to managing energy consumption in smart buildings. By integrating IoT sensors, rule-based automation and carbon-aware optimization, the system ensures effective utilization of energy while minimizing wastage and reducing environmental impact.

The system not only reduces electricity costs but also promotes sustainable energy practices by considering carbon emissions in its decision-making process. The use of real-time data and automated control enhances system performance and reduces the need for manual intervention.

In addition, the system promotes sustainability by incorporating carbon-aware decision-making and reducing electricity



International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

costs. It enhances user convenience through automation and monitoring, making it a reliable and eco-friendly approach to modern energy management.

REFERENCES

- [1] L. U. G. Ekanayaka Gunasinghalge, A. Alazab, and M. A. Talukder, "Artificial Intelligence for Energy Optimization in Smart Buildings: A Systematic Review and Meta-Analysis," *Energy Informatics*, vol. 8, 2025, Springer.
- [2] Joaquín Delgado Fernández, "AI-Driven Sustainable Smart Building Optimization Framework," *Springer Journal*, 2025.
- [3] Y. Wei et al., "Deep Reinforcement Learning for HVAC Control in Smart Buildings," *IEEE Transactions on Smart Grid*, 2024.
- [4] Z. Zhang et al., "Federated Learning for Privacy-Preserving Energy Management in Smart Buildings," *IEEE Transactions on Smart Grid*, 2024.
- [5] S. Ruelens et al., "Multi-Agent Reinforcement Learning for Demand Response in Smart Grids," *IEEE Transactions on Smart Grid*, 2023.
- [6] M. Ahmad et al., "LSTM-Based Building Energy Load Forecasting," *IEEE Access*, 2023.
- [7] X. Chen et al., "Edge AI-Based Intelligent Energy Management System for Smart Buildings," *IEEE Internet of Things Journal*, 2022.
- [8] Y. Deng and H. Chen, "IoT and Machine Learning-Based Smart Energy Management Framework," *IEEE Internet of Things Journal*, 2021.
- [9] H. Wang et al., "Reinforcement Learning for Smart Grid Energy Optimization," *IEEE Transactions on Smart Grid*, 2021.
- [10] T. Wei, Y. Wang, and Q. Zhu, "Deep Reinforcement Learning for Building HVAC Control," *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 1–10, 2020.
- [11] B. McMahan et al., "Communication-Efficient Learning of Deep Networks from Decentralized Data," in *Proc. IEEE AISTATS*, 2017.
- [12] Q. Yang, Y. Liu, T. Chen, and Y. Tong, "Federated Machine Learning: Concept and Applications," *ACM Transactions on Intelligent Systems and Technology*, 2019.
- [13] . Zhou, X. Chen, E. Li, L. Zeng, K. Luo, and J. Zhang, "Edge Intelligence: Paving the Last Mile of Artificial Intelligence with Edge Computing," *Proceedings of the IEEE*, 2019.
- [14] J. Kleissl and Y. Agarwal, "Cyber-Physical Energy Systems for Smart Buildings," *Energy and Buildings*, Elsevier, 2016.



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH IN SCIENCE, ENGINEERING AND TECHNOLOGY

| Mobile No: +91-6381907438 | Whatsapp: +91-6381907438 | ijmrset@gmail.com |

www.ijmrset.com