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Leveraging green IoT to enhance energy-saving efficiency in fairness-oriented residential photovoltaic charging stations

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Abstract
As electric vehicles (EVs) continue to gain global popularity, residential photovoltaic (PV) charging stations are becoming more common, providing a sustainable way to charge EVs. However, the intermittent nature of solar energy creates challenges in ensuring consistent and fair charging, making fairness-based charging scheduling essential. To automate this process, residential PV charging stations require a customized Internet of Things (IoT) system. A significant concern is the substantial energy consumption due to the high volume of data transmission within the IoT system. This research aims to enhance energy efficiency by leveraging green IoT strategies suitable for such applications. The study proposes the use of edge computing, optimized data transmission scheduling, and delta compression techniques at the edge to minimize energy use. The results demonstrate that these strategies are effective in achieving energy savings. Energy-saving efficiency on the source side ranges from 1.96% to 7.84%, while on the load side, it ranges from 57.5% to 61.3%. These findings highlight the effectiveness of the proposed strategies in reducing energy consumption, providing an efficient solution for optimizing data transmission in residential PV charging stations. Overall, the strategies contribute to the sustainable operation of electric vehicle charging infrastructure by improving energy efficiency and ensuring fair distribution of charging resources.

1. Introduction

In residential photovoltaic (PV) charging stations, fairness charging method is a crucial due to energy limitations. In [1], an energy distribution strategy is proposed to ensure that the PV energy is distributed equitably among all electric vehicle (EV) owners. As the result, the satisfaction of EV owners can be improved. Figure 1 shows the proposed residential PV charging station system models. The electric power system in this model requires further development in terms of automated communication between the source and the load. Therefore, the residential PV charging station is enhanced by integrating a modern Internet of Things (IoT)-based communication framework that connects PV generation, EV charging scheduling, the IoT system, and fairness-oriented EV charging control.

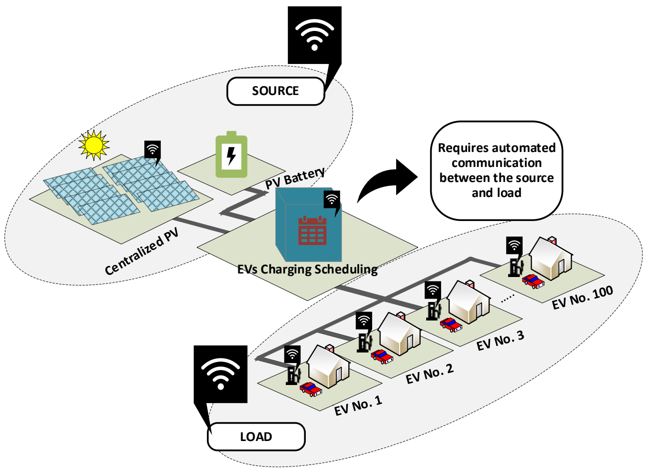


Figure 1. The Residential PV Charging Station System Models

Addressing that essential, IoT concept could provide an appropriate solution to support automated systems. The IoT has produced an increasingly dynamic impact worldwide due to its advanced technology mechanisms in scientific disciplines, including the field of charging stations. In [2][3], IoT was implemented to manage the power distribution for electric vehicle (EV) charging. In [4][5][6], the smart charging station was developed by implementing IoT, which able to reduce the time needed to find a charging station. In [7], a smart charging method was introduced to increase the utilization of renewable resources while reducing reliance on the main grid. Meanwhile, in [8][9], IoT was integrated with the charging station to schedule charging times while considering energy resources.

Additionally, IoT offers the ability to manage both demand and supply by managing generation and demand for improved performance. The IoT emerge as an important partner in resource and energy management [10][11][12][13]. In [10], IoT for demand side management (DSM) was proposed a smart energy management system (SEMS). In [14], an Intelligent Power Management System (IPMS) is designed to compensate for the energy loss in a region with managed partial load reduction that meets consumption habits and price. IPMS uses an IoT framework for predictive analytics and archiving. Meanwhile the [15] overcomes the additional load from EVs at peak times. At peak time, the EV is effectively charged by grid which connected with PV. Besides that, EV also acts as uninterrupted power supply (UPS) based on time of use (ToU) tariff. IoT takes an intelligent approach to managing field operations to make appropriate decisions and management [16]. In this system, IoT is proposed to handle the monitoring and control process. The IoT technology is responsible for processing data and performing comprehensive data analysis.

However, IoT application typically generate continuous and large volumes of data. As a result, large data volumes that must be transmitted over constrainted networks. This condition leads to increased transmission latency, limited bandwidth availability, and intensive computational load during data processing. Consequently, these challenges contribute to significant energy consumption in IoT devices [17][18][19][20][21][22][23]. Furthermore, IoT systems are expected to operate reliably over long periods. Therefore, efficient data transmission becomes a critical requirement. In [24], the study focuses on extending the coverage of LoRa networks through multi-hop uplink communication, while simultaneously aiming to minimize energy consumption by optimizing the transmission power at each hop to the lowest effective dBm level. However, further improvement is needed by also considering the reduction of transmitted data volume, as data size significantly contributes to overall energy consumption in IoT systems. Therefore, energy management strategies for IoT should be considered. This is essential for achieving energy efficiency and reliability. In [25], IoT energy-efficiency must be consider from the design step to implementation. The focus on energy-efficiency in IoT is referred to as green-IoT [26][27][28].

In [29] and [30], energy efficiency was realized through hardware-based approaches. In [29], interpolation was performed to reduce the number of required sensors. Meanwhile, in [30], the optimal placement of IoT gateways was employed using genetic algorithm (GA) to reduce the number of IoT gateways while maintaining system performance.

Moreover, achieving energy efficiency through software-based approach is crucial. In [17], machine learning was proposed as a method to enhance IoT energy efficiency using edge computing. A fast error-bounded lossy compressor is applied before transmitting the data. The transmitted data is reconstructed using supervised machine learning on the edge node. In [31], an Energy Management Scheme (EMS) was proposed with three strategies to maintaining an ideal energy consumption. The first strategy is data minimization which will be transmit trough IoT. The second strategy is scheduling the task based on priority. The third strategy is fault tolerance that can replace a failure node with an alternative node. Then, the studies continue focuses on reducing transmission data. In [32], a two-tier data reduction technique was implemented on sensor nodes and gateway. Meanwhile in [33], the data compression is analyzed in relation to energy consumption. However, their approaches remain limited to data-size minimization and do not provide a comprehensive mechanism to address long-term energy efficiency in continuous IoT operations. Similarly, studies in [22] and [34] apply delta compression to eliminate redundant data. In [22], a new coding scheme was proposed for IoT sytem but still relies on TinyOS (TOS) packets, which are incompatible with major cloud IoT platforms. While [34] evaluates delta compression for backup systems, it does not consider real-time IoT requirements. Although several studies have addressed energy saving in IoT by reducing the volume of transmitted data, significant gaps remain. The previous research has not offered an integrated solution that combines enegy-efficient transmission, real-time operability, and cloud-compatability. To address these limitations, this research introduces a novel green IoT approach that integrates edge computing, scheduling data transmission, delta compression, and MQTT to ensure cloud compatibility. This integrated method provides a more comprehensive solution for reducing energy consumption, and it is particularly essential for fairness-oriented charging in residential PV charging stations case study. This research proposes four key reseach to achieve green IoT at residential PV charging station.

a. Identify the appropriate IoT architecture for the case study to achieve fairness-oriented charging at residential PV charging station.
b. Design of integrated green IoT strategies that combine edge computing, scheduling-based data transmission, and delta compression.
c. Minimize energy consumption during data transmission in the IoT system by optimizing both the volume and timing of transmitted data.

d. Conduct a comprehensive examination of the energy-saving efficiency of the proposed green IoT strategies in the case study.

The remainder of this article is organized as follows. Section 2 discusses about the research method. Section 3 details the results and discussion. Finally, section 4 provides the conclusion of this research.

2. Research Method

The system architecture is designed to facilitate the automated implementation of fairness charging scheduling at residential PV charging station. Figure 2 display the IoT system model for the case study. This design requires an IoT system to effectively manage and coordinate various components, including PV systems, EVs, and data processing units. In order to present the IoT system, it is essential to recognize the actual system model. On the source power side, temperature, humidity, and irradiance sensors are connected to the PV system. Then, the edge device calculates the PV power value based on the sensors' information. The edge device as data aggregator calculates the average value of each sensor for hourly data before sending it to cloud. On the load side, current and voltage sensors are connected to EVs battery. Then, the edge device calculates the SoC of each EV battery. On the cloud side, cloud computing will predict the solar irradiation and SoC of each EV battery on day-ahead. The cloud also schedules the EV charging using artificial intelligent. The edge device on the load side will receive charging instructions based on the cloud computing result.

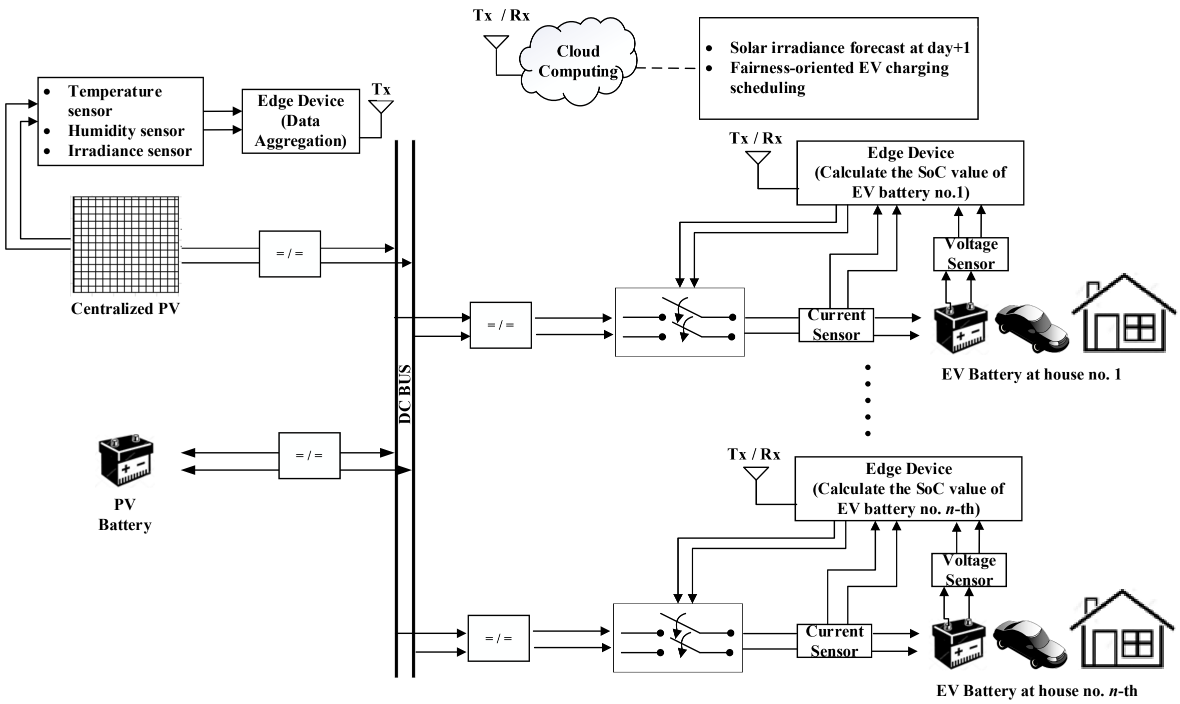


Figure 2. The IoT System Model

Set $(A) = \{A_1, A_2, \dots, A_i\}$ be the set of *i* number of EV. A_i is denotes the *i*-th EV. Then, set $(T) = \{T_1, T_2, \dots, T_t\}$ be the set of *t* hourly time in a day. The power rate of EV charging is contained in set $(D) = \{D_1, D_2, \dots, D_i\}$. The total demand requirement for all EVs is given in set $(L) = \{L_1, L_2, \dots, L_i\}$. Therefore, the EVs charging scheduling decision is formulated in Equation 1. $C_{i,t}$ is decision variable. The variable *i* denotes EV and *j* represent time hourly. If the decision in *i*-th is scheduled charging at *t*-th time then the $C_{i,t} = 1$, otherwise $C_{i,t} = 0$.

$$C = \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,t} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,t} \\ \vdots & \vdots & \vdots & \vdots \\ C_{i,1} & C_{i,2} & \cdots & C_{i,t} \end{bmatrix} \quad (1)$$

2.1 Objective Function

In order to optimize IoT system, minimizing the volume of data transmission is crucial for enhancing energy-saving efficiency in IoT system. The objective function for this problem focuses on reducing the amount of data that needs to be transmitted across the network while ensuring that system performance and reliability are maintained. Therefore, the objective function of this research present in Equation 2.

$$F_{(objective)} \Rightarrow \min\left(\sum_{s=1}^{N} D_s(t)\right), \qquad 1 \leq t \leq 24 \tag{2}$$

In the Equation 2, s denotes sequential of s^{th} strategies, N is the number of proposed strategies of green IoT, t is an integer representing the hourly time within a day, and $D_s(t)$ is the volume of data transmitted (bits).

2.2 Identify the IoT Architecture

The pre-identified data requires an appropriate IoT system. The next step is to identify the IoT architecture required for the case study. Figure 3 presents the coordinated framework of EVs charging scheduling. The framework shows interaction among the PV source network, the scheduling platform, and the EV charging network. Charging demand, scheduling decisions, and source information are exchanged to enable fairness-oriented charging management. The scheduling platform obtains EV SoC battery data from the charging network and PV power data from the source network. Based on the data, the scheduling platform will forecast PV power on day-ahead. If the day-ahead forecast PV power is less than EV power requirements, the scheduling platform actives fairness charging for all EVs.

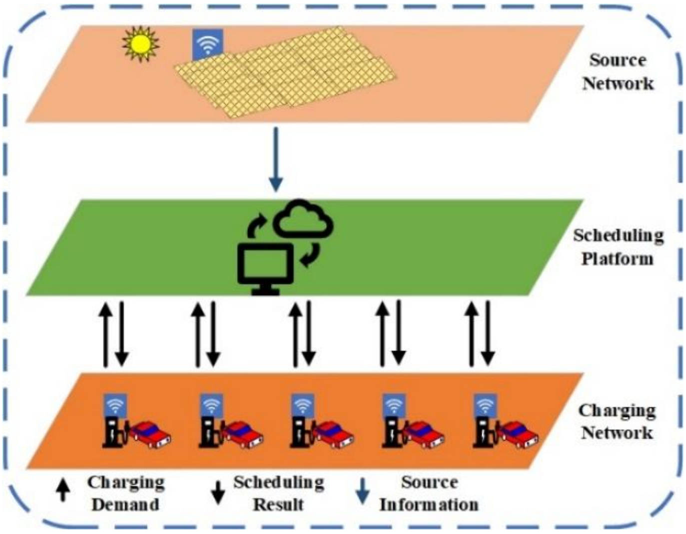


Figure 3. The Coordinated Framework of EVs Charging Scheduling

The proposed IoT architecture is organized into multitier tiers described in the multitier IoT architecture layers. Multitier IoT architecture layers represent a specific design approach for developing each function and interaction within the IoT system. The proposed multitier IoT layers can be seen in Figure 4. Tier 1 (Physical Device) consists of multiple EVs and a centralized PV, each connected to a microprocessor with internet capability. The information from these devices is forwarded to the edge computing. This layer also receives information related to EV charging scheduling decisions. Tier 2 (Edge Computing) enables real-time data processing and on-site data filtering which close to the data source. Edge computing reduces the volume data transmission. On the source side, edge computing serves as a data aggregator to calculate the hourly average value of solar irradiance, temperature, and humidity. Meanwhile, on the load side, edge computing is used to calculate SoC of all EV batteries. Tier 3 (Local IoT Gateway) functions as a link between IoT devices connected to a local network and the cloud or a larger IoT platform. Tier 4 (Cloud Computing) enables complex data processing such as predictive analytics, machine learning, or artificial intelligence algorithms to extract valuable information from data received from IoT devices. Tier 5 (Data Processing Analysis) is processed in cloud computing. The data analysis is for forecasting total energy and fairness EV charging scheduling with artificial intelligent on day-ahead. Tier 6 (Visualization) is result of the data processing action. The action is to control the EV charging switch.

Meanwhile, Figure 5 presents the method architecture and algorithm flowchart of the proposed green-IoT system, which integrates edge computing, scheduling-based data transmission, and delta compression to reduce energy consumption in fairness-oriented EV charging. At the device level, edge computing performs local processing and data filtering on EV and PV measurements, thereby reducing raw data volume before transmission. The scheduling regulates when the processed data are uploaded. Delta compression is applied to further reduce the size of transmitted data.

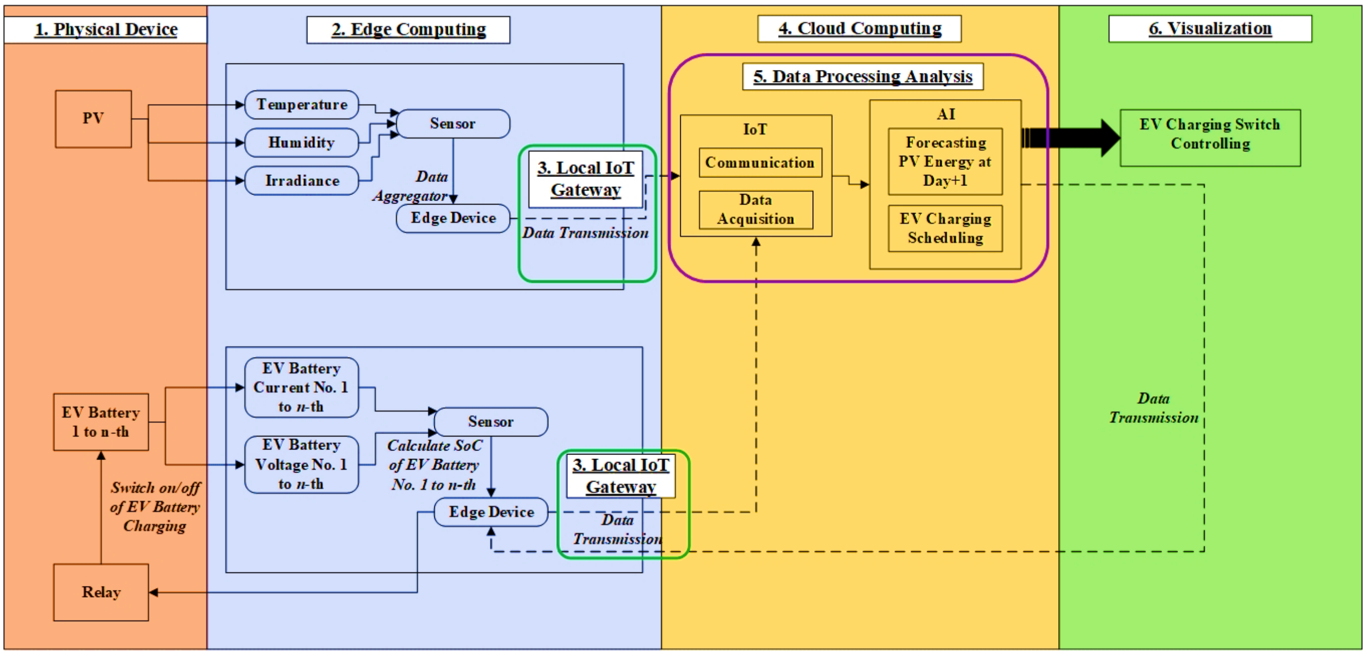


Figure 4. Multitier IoT Layer Architecture

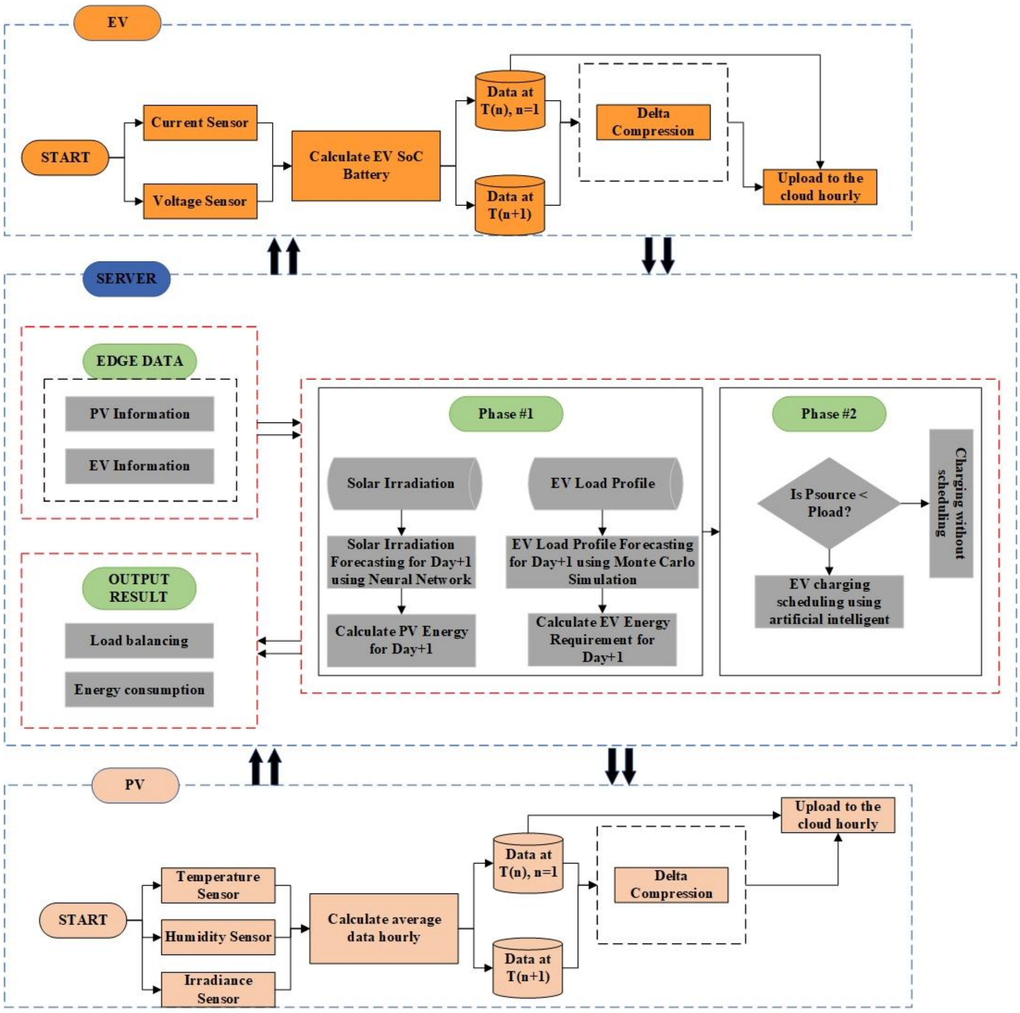


Figure 5. Method Architecture and Algorithm Flowchart

2.3 Edge Computing Strategy

Based on the IoT architecture designed for the case study system, edge computing is an effectively strategy to reduce the energy requirements in IoT system. An important action to enhance energy-saving efficiency in IoT system is move the computational tasks from cloud to the edge. Data processing can be handled by edge computing to avoid transmitting it to the cloud. Edge computing enables data processing and local decision making. Therefore, edge computing benefits to reduce data transmit, saving time, saving energy, and bandwidth efficiency. In the case study system, there are hardware components that needed to measured using sensors. The amount of data from sensors is explosive. The utilization of edge computing is an attractive solution. Edge computing is responsible for processing the data into desire format at each hardware component. Some of the tasks that can be processed in edge computing include data aggregation from sensors, SoC of each EV battery, delta compression, and scheduling data transmission.

2.4 Sensor Data Processing

On the source side, the data from the sensors are consists of temperature, humidity, and solar irradiance. Therefore, edge computing is needed as data aggregation. The average data will be calculated hourly to serve as representative data. The data transmitted is used for forecasting the solar irradiation for day-ahead. The forecast solar irradiation data will determine whether intermittency occurs. When the intermittent occur, the load scheduling will be implemented to fairness-oriented charging at residential PV charging stations.

Meanwhile, on the load side, sensor data is obtained from two sensors. Edge computing plays a role in reducing data transmission into one data by processing the data into a single output. The SoC of each EV battery data is an important data for forecasting the EV load profile. The SoC of EV battery is calculated using the following Equation 3.

$$SoC_{EV_i} = \frac{E_{EV_i}}{C_{EV\ battery_i}} \times 100\% \quad (3)$$

In Equation 3, SoC_{EV_i} is the SoC of EV $i-th$. E_{EV_i} is the energy of EV battery $i-th$ and $C_{EV\ battery_i}$ is the battery capacity of EV $i-th$.

2.5 Scheduling Data Transmission Strategy

In this case study, continuous data transmission is not efficient because the system is investigated hourly. Therefore, data transmission can be performed periodically to alleviate the issue. This approach allows for frequent data synchronization while minimizing the amount of data transmitted. As a result, the hourly data transmission facilitates a way to achieve energy-saving efficiency.

2.6 Delta Compression Strategy

Data compression is considered as an important process for reducing the size of transmitted data in IoT environments. The energy required for data transmission can be reduced through data compression technique. Data compression can reduce the number of bits transmitted. In this study, delta compression is used to compress the data that will be transmitted. Delta compression can improve the efficiency of data transmission through data management techniques. This compression method focuses on transmitting the differences between successive versions of data, rather than transmitting the entire data. The formula for delta compression is provided below (Equation 4).

$$\Delta D = D_{t+1} - D_t, \quad 1 \leq t \leq 24 \quad (4)$$

In Equation 4, ΔD is delta or difference number of bits data transmitted, D_{t+1} is number of bits for data in *t+1* and D_t is number of bits for data in *t*.

2.7 MQTT Protocol

The Message Queue Telemetry Transport (MQTT) protocol is a publish/subscribe messaging protocol designed for efficient communications in environments with limited bandwidth or unreliable network. Therefore, this research implements MQTT as the communication protocol for message exchange. The MQTT standard packet structure is describe in the following Figure 6.

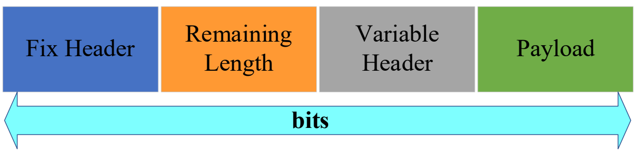


Figure 6. MQTT Standard Packet Structure

The fix header provides essential information about the packet, such as message type, flags, and packet identifier. Remaining length indicates the total length of the remaining data in the MQTT packet. The variable header contains additional information specific to the message type. The payload contains the actual message content being sent or received.

2.8 Enery-Saving Efficiency

Energy-saving efficiency refers to using less energy to achieve the same level of service or output. Implementing the proposed green IoT strategies at residential PV charging stations is an effective way to reduce the energy required for data transmission. The energy required for data transmission is illustrated in Figure 7 and calculated using Equation 5 [35].

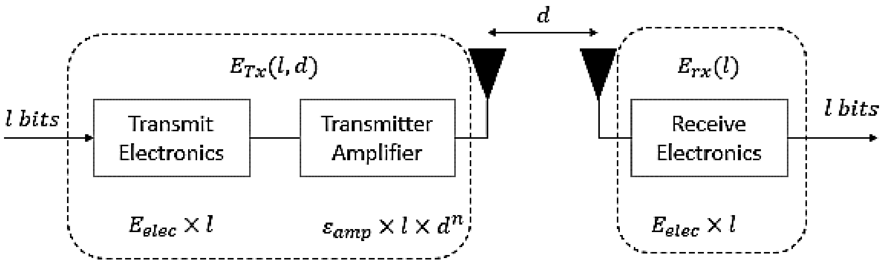


Figure 7. IoT Energy for Transmission Model

$$E_{total}\ (J) = l\ (bits)\ \times E_{bit}\ \left({}^{J}/_{bit}\right) \tag{5}$$

$$E_{bit} = E_{elec}N + E_{DA}N + k\varepsilon_{mp}d^{4}{}_{to\ BS} + E_{elec}N + \varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k}N \tag{6}$$

In Equation 5 E_{total} is total energy, l is the amount of data, and E_{bit} is energy per bit. In Equation 6, E_{elec} is electronics energy, N is number of nodes, E_{DA} is energy for data aggregation, k is clusters, ε_{mp} and ε_{fs} are amplifier energy when the distance is larger than threshold distance $(d \geq d_0)$ and the distance is shorter than threshold distance $(d < d_0)$, respectively. Then, $d_{to\ BS}$ is the distance from cluster head node to base station and M is the region. Meanwhile, the energy-saving efficiency is calculated by the following Equation 7.

$$\eta = \left(1 - \frac{E_g}{E_0}\right) \times 100\% \tag{7}$$

Where η is energy-saving efficiency, E_g and E_0 are the total energy for transmission with and without green IoT strategies, respectively.

2.9 Parameter Setting

The proposed green IoT strategies for implementing fairness charging at residential charging stations are simulated to analyse their effectiveness. The load consists of 100 EVs with 7 types of private car EVs. As initial simulation, the sensor data is obtained from the Global Solar Atlas and AccuWeather websites. The distribution of residential charging demand was executed using a Monte Carlo simulation. The Monte Carlo simulation result is presented in Figures 8 and 9. Meanwhile, the rest parameters setting present in Table 1. These parameters are essential for ensuring that proposed system functions optimally while addressing real-world constraints.

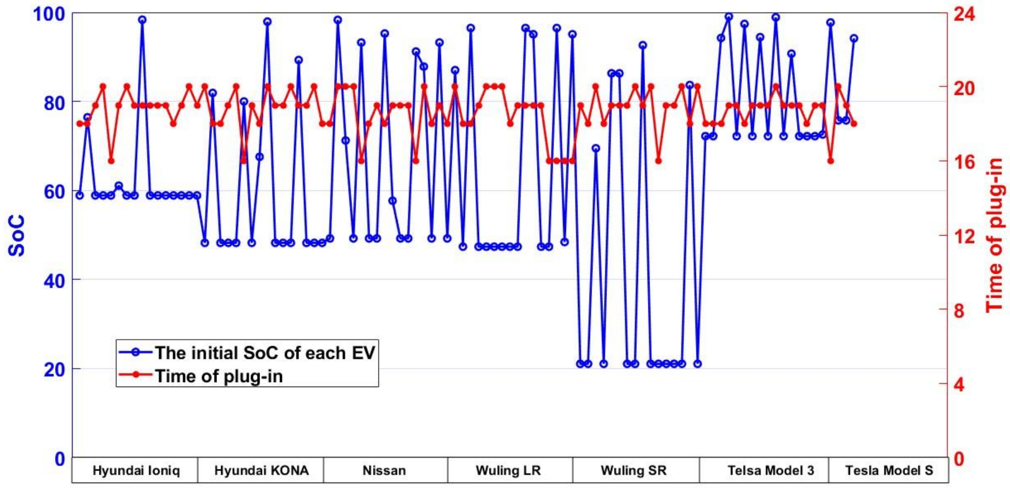


Figure 8. The Distribution of All EV Types

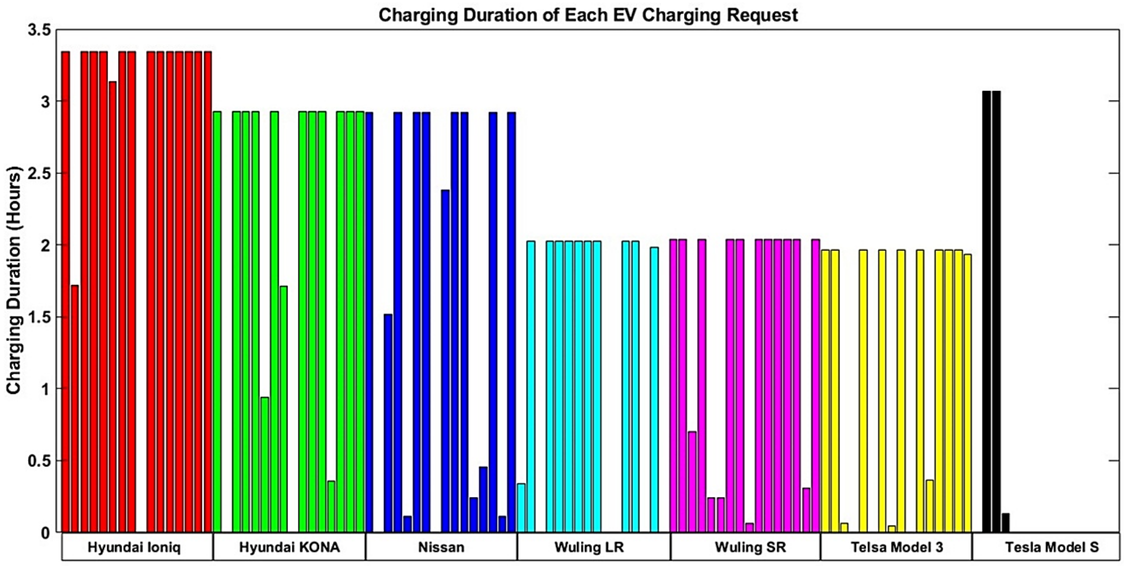


Figure 9. Charging Duration of All EVs

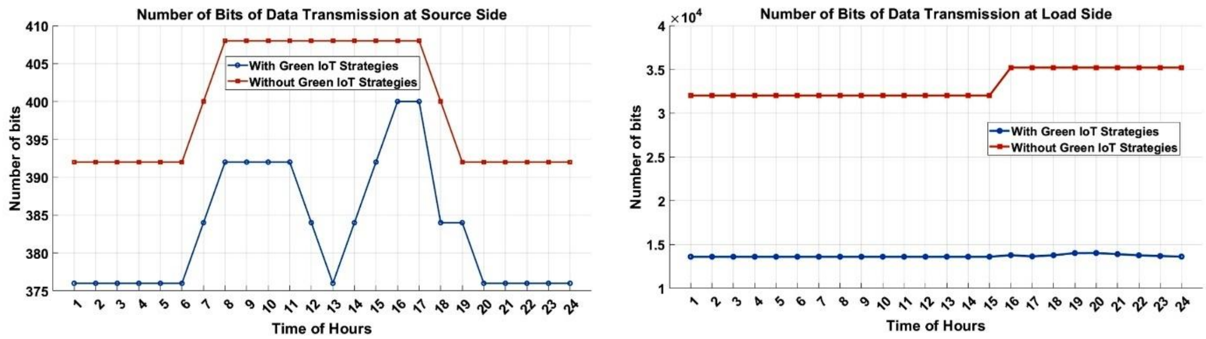
Table 1. Parameter Setting [35][36][37]

Parameter	Value
E_{elec}	$50\ nJ/bit$
E_{DA}	$5\ nJ/bit/signal$
N	$100\ nodes$
k	$1 < k < 6$
ε_{mp}	$0.0013\ pJ/bit/m^4$
ε_{fs}	$10\ pJ/bit/m^2$
$d_{to\ BS}$	$75\ m < d_{to\ BS} < 185\ m$
M	$100\ m$
Bandwidth allocation	54 Mbps

3. Results and Discussion

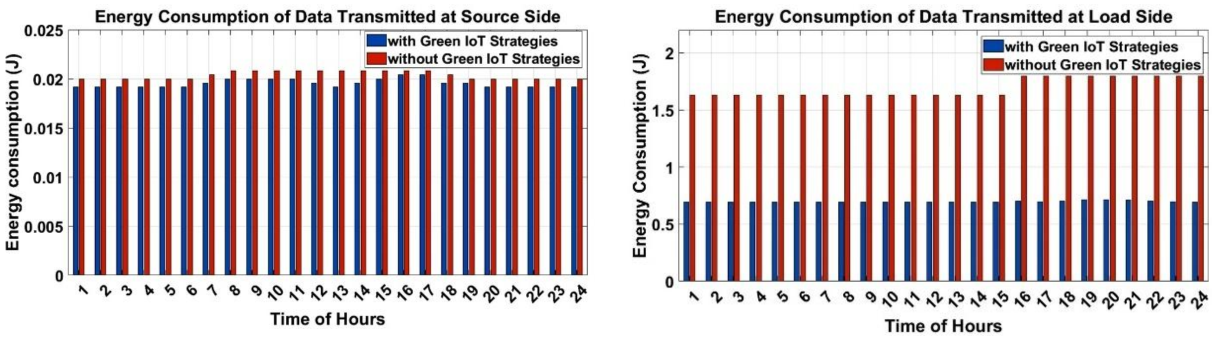
This section presents the results of implementing green IoT strategies for fairness charging at residential PV charging stations as the case study. In this research, designing a green IoT strategies aimed to minimizing the volume of data transmitted through IoT systems. The reduction in data transmission is expected to enhance energy-saving efficiency in the automated implementation of the case study.

The strategy involves applying sensor data processing, scheduling data transmission, and delta compression on edge computing for both the source and load sides. The simulation of energy consumption is processed according to parameter setting in Table 1. Edge computing plays a key role in this process. The comparison of number of bits with and without green IoT strategies is presented in Figures 10.a and 10.b. Figure 10.a shows the variation in the number of bits transmitted at the source side over a 24-hour period under two scenarios: with and without Green IoT strategies. The results show that the without Green IoT strategies case consistently maintains a higher number of transmitted bits, ranging from approximately 392 to 408 bits, with peak values sustained between 08:00 and 17:00 hours. In contrast, the with Green IoT strategies scenario demonstrates a lower and more fluctuating transmission pattern, ranging from about 376 to 400 bits, with peak values occurring around 16:00–17:00 hours and minimum values observed during off-peak hours (01:00–06:00 and 20:00–24:00). On average, the Green IoT approach reduces the number of transmitted bits compared to the non-Green IoT case, indicating a potential reduction in energy consumption and data load at the source side. Meanwhile, Figure 10.b presents the number of bits transmitted at the load side over a 24-hour period for both scenarios: with and without Green IoT strategies. In the without Green IoT strategies case, the number of transmitted bits remains stable at approximately 3.2×10^4 bits from 01:00 to 15:00 hours, before increasing to around 3.52×10^4 bits from 16:00 onwards. Conversely, the with Green IoT strategies case maintains a substantially lower transmission rate, averaging around 1.4×10^4 bits throughout the day, with only minor fluctuations and a slight peak occurring near 16:00 hours. The comparison indicates that implementing Green IoT strategies can reduce the transmission volume at the load side by more than 50% compared to the non-Green IoT scenario, representing a significant potential reduction in communication overhead and energy usage. The reduction in data volume impacts to energy consumption and energy-saving efficiency. Figures. 11.a and 11.b demonstrates this effect.



(a) (b)

Figure 10. The Number of Bits of Data Transmitted Using Green IoT Strategies (a) on the Source Side (b) on the Load Side with $d_{to\ BS}$ =75 m and N=100 Nodes



(a) (b)

Figure 11. The Energy Consumption of Data Transmitted Using Green IoT Strategies (a) on the Source Side (b) on the Load Side with $d_{to\ BS}$ =75 m and N=100 Nodes

Figure 12 shows the total of energy-saving efficiency, as determined by the objective function, after implementing the proposed green IoT strategies. The implementation of the proposed strategies lead to substantial energy saving on both the source and load sides. The energy saving efficiency (η) at both the source side and load side over a 24-hour period. The load side consistently achieves substantially higher efficiency values, maintaining approximately 57.5–61.3% throughout the day, with a slight increase observed from 16:00 onwards. In contrast, the source side exhibits much lower efficiency levels, generally ranging between 1.96% and 7.84%. The significant gap between the two curves highlights that the majority of energy savings are realized at the load side when implementing Green IoT strategies.

This implies that optimizing data transmission at the load side contributes more substantially to overall energy conservation compared to the source side, although both play complementary roles in achieving system-wide efficiency improvements. This indicates that implementing the strategies for fairness charging at residential PV charging station, as the case study, can affectively realize the goals of green IoT.

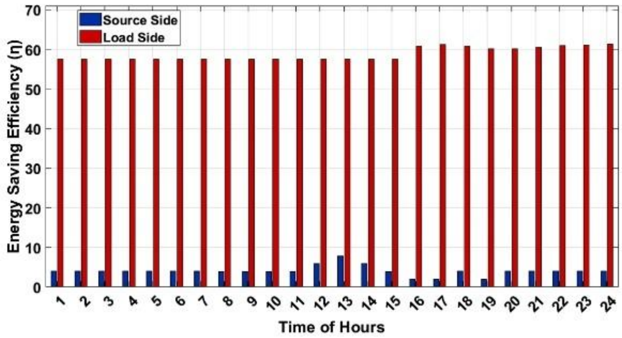


Figure 12. The Total of Energy-saving Efficiency

From a broader perspective, the results highlight several implications. First, improving transmission efficiency contributes to long-term IoT sustainability by lowering device energy consumption and potentially extending the operational lifespan of system components. Second, the outcomes provide a valuable reference for future EV charging infrastructure that relies on cloud-based connectivity, where minimizing energy consumtion is essential. Analytically, the substantial difference between load side and source side efficiencies indicates that load side data optimization plays the dominant role in reducing energy consumption. This aligns with findings in prior studies that emphasize the importance of compression at the devie level, but those studies typically investigate only a single green IoT technique [17][22][32][33][34]. In contrast, our results demonstrate that combining multiple strategies. In addition, these results provide significant new directions for the design of future EV charging infrastructure that requires cloud connectivity with minimal energy consumption.

4. Conclusion

This research has examined the proposed green IoT strategies for achieving energy savings at fairness-based residential PV charging stations. The designed IoT architecture helps identify opportunities for each green IoT strategy. The result show that utilizes edge computing to implement green IoT strategies can significantly reduce the number of bits transmitted. The combination of all proposed strategies leads to significant the total energy-saving efficiency. The total energy-saving efficiency on the source side range from 1.96% to 7.84%, while on the load side, it ranges from 57.5% to 61.3%. These findings indicate that the proposed integrated strategies are effective for supporting green IoT implementation in fairness-oriented residential PV charging stations systems.

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