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Smart and Sustainable Wireless Electric Vehicle Charging Strategy with Renewable Energy and Internet of Things Integration

Sheeraz Iqbal [1], Nahar F. Alshammari [2], Mokhtar Shouran [3,4] and Jabir Massoud [5,*]

1 Department of Electrical Engineering, University of Azad Jammu and Kashmir, Muzaffarabad 13100, AJK, Pakistan
2 Department of Electrical Engineering, Faculty of Engineering, Jouf University, Sakaka 72388, Saudi Arabia
3 Libyan Center for Engineering Research and Information Technology, Bani Walid, Libya
4 Department of Control Engineering, College of Electronics Technology, Bani Walid P.O. Box 38645, Libya
5 School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
* Correspondence: massoudj1@cardiff.ac.uk

Abstract: This study addresses the challenges associated with electric vehicle (EV) charging in office environments. These challenges include (1) reliance on manual cable connections, (2) constrained charging options, (3) safety concerns with cable management, and (4) the lack of dynamic charging capabilities. This research focuses on an innovative wireless power transfer (WPT) system specifically designed for use in office parking areas. This system incorporates renewable energy resources (RERs) and uses the transformative power of the Internet of Things (IoT). It employs a mix of solar energy systems and battery storage solutions to facilitate a sustainable and efficient energy supply to EVs. The integration of IoT technology allows for the automatic initiation of charging as soon as an EV is parked. Additionally, the implementation of the Blynk application offers users real-time access to information regarding the operational status of the photovoltaic system and the battery levels of their EVs. The system is further enhanced with IoT and RFID technologies to provide dynamic updates on the availability of charging slots and to implement strict security protocols for user authentication and protection. The research also includes a case study focusing on the application of this charging system in office settings. The case study achieves a 95.9% IRR, lower NPC of USD 1.52 million, and 56.7% power contribution by RERs, and it reduces annual carbon emissions to 173,956 kg CO_2.

Keywords: wireless EVs charging station; electrical vehicles; wireless power transfer; IoT; renewable energy resources

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1. Introduction

1.1. Background and Motivation

The pressing urgency of global climate change has illuminated the profound need for transitions toward sustainable energy frameworks. Predicated on the dual challenges of environmental preservation and the inevitable depletion of fossil fuels, the world's energy focus is undergoing a transformative shift [1]. This transition restructures how societies conceptualize energy consumption, production, and distribution. A vital component of this restructuring is the dominance of electric vehicles (EVs). Traditional combustion engine vehicles rely heavily on non-renewable fuels and contribute substantially to global CO_2 emissions. In contrast, EVs offer a more environmentally gentle transportation option [2]. Their growth in popularity signifies not only a technological evolution but also an emerging societal acknowledgment of the need for sustainable practices. However, the momentum behind EVs is not solely a product of their environmental merits [3]. The viability of EVs, like any technological innovation, depends on a supportive and efficient infrastructure. The charging station, in this respect, is similar to the petrol station of the past century.

Without accessible and efficient charging solutions, the widespread adoption of EVs could face significant barriers [4].

In charging solutions, solar-powered charging stations represent the intersection of two sustainable technologies. One is solar energy harvesting and the other is electric transportation. Solar-based charging stations offer an elegant solution to some of the challenges associated with EV charging, such as grid dependence and energy source sustainability [5]. Moreover, solar energy, given its renewable nature, aligns with EVs. The traditional grid-based charging stations often draw power from non-renewable sources. In contrast, solar charging stations exemplify a more general approach to sustainable transportation, sourcing energy directly from the environment [6]. The operational efficiency of these stations, however, extends beyond just energy sourcing. The latest technological advancements in solar energy storage, conversion, and transfer can dramatically affect the user experience. From reduced charging times to increased energy storage, capacities are continually being expanded [7]. The solar-powered charging station in this study is not a fixed design but rather an exhibition of a quickly developing technical environment [8]. In addition, in an increasingly linked digital era, the use of technology such as the Internet of Things (IoT) and sophisticated security systems is not only advantageous but necessary. The contemporary user desires not just practicality but also the additional advantages of interaction, real-time data, and security. Given this understanding, the suggested charging station integrates these components, hence augmenting its value proposition [9].

1.2. Wireless Power Transfer (WPT)

Traditional charging techniques for electric vehicles (EVs) that include physical connections provide several difficulties for users. Frequently, the degradation of cables and plugs needs regular replacements and maintenance. Furthermore, they express apprehensions about the safety and efficacy of electricity transmission. Moreover, the inherent security measures of these systems restrict the freedom and flexibility of vehicle location when charging [10]. In addition to convenience, these limitations might often discourage prospective electric vehicle (EV) customers who prioritize straightforwardness and dependability in their daily encounters [11]. On the other hand, WPT signifies a fundamental change in the method of supplying electricity to electric vehicles. Stemming from the core concepts of electromagnetic induction, WPT systems deploy coils, one in the charging station and one in the vehicle, to assist the transmission of energy over an air gap. This lack of physical connections greatly minimizes the risks of wear-induced inefficiencies and dangers. This provides a more lasting and reliable power supply method [12]. Moreover, the simplicity of WPT serves as a tribute to its user-centric approach. By only parking the car close to a WPT-enabled charging station, customers may commence the charging process, free from the disruption of handling wires or aligning plugs [13].

Another advantage of WPT is its potential to redefine the concept of a charging station. Traditional charging stations are often envisioned as designated spots where vehicles must remain stationary for extended durations. With WPT, however, there is the potential to insert charging mechanisms in a variety of infrastructures. From parking spots in malls or offices to specialized lanes on highways where vehicles can be charged on the go [14]. Such innovations could revolutionize the EV charging ecosystem, making charging a more passive, integrated, and seamless activity rather than a distinct, time-consuming task. Furthermore, the scalability and flexible nature of WPT systems present vast opportunities for integration with other sustainable technologies. Imagine a scenario where solar arrays directly feed into WPT-enabled charging hubs, allowing for the real-time conversion and transfer of solar energy to vehicles [15]. Such integrations could further the sustainability agenda while maximizing the utility derived from RERs. In essence, the advent of WPT is not just an incremental upgrade to the existing EV charging framework; it is a transformative dive. By addressing the core challenges of conventional charging and adding layers of convenience and flexibility, WPT reshapes the future of EV charging. It makes it more user-friendly, efficient, and integrated with everyday experiences [16].

1.3. Importance of Automated Charging Mechanisms

In today's fast-paced world, automation is becoming an expectation in many sectors. Historically, numerous systems and processes required thorough human intervention. This often leads to inconsistencies and inefficiencies stemming from human error [17]. For EV charging, automation takes on a nuanced significance [18,19]. Instead of drivers needing to manually adjust settings or monitor their vehicle's charging status consistently, an intelligent automated system can gauge the vehicle's requirements, adjusting in real-time to changes in prevailing conditions. Such adaptability ensures that EVs are not just charged but charged optimally, maximizing battery longevity and ensuring vehicle readiness [20].

1.4. Ensuring Reliability: Monitoring the Photovoltaic (PV) Modules

The appeal of solar power lies in its sustainability. However, its efficacy as a consistent energy source relies heavily on the performance of PV modules. These modules, responsible for converting sunlight into usable electricity, are subject to wear, environmental impacts, and potential technical malfunctions [21]. Thus, without diligent monitoring, the very foundation of a solar-powered charging station can be compromised. A dedicated monitoring system for PV modules serves dual purposes. First, tracking performance metrics in real-time ensures that the solar panels operate at peak efficiency, translating to consistent and dependable energy output [22]. Second, an early detection system can identify potential issues, allowing for proactive maintenance and reducing downtime. In a world where reliability can significantly impact user trust and adoption rates, such monitoring becomes indispensable [23].

1.5. Introducing Modern Connectivity: The Role of IoT

The digital age has been accompanied by an era of extraordinary connectivity. The IoT characterizes this trend, weaving a network of interconnected devices that communicate, share data, and optimize operations based on real-time feedback [24]. Within a solar-powered charging station, the integration of IoT can redefine user interaction. By embedding sensors and communication modules, the charging station can provide users with instantaneous feedback on various parameters, from charging progress to grid health [25]. Furthermore, such integration allows for remote monitoring, where users can check charging status, reserve slots, or even schedule charging sessions via smartphone applications [26]. This level of transparency does not just enhance user experience; it fosters a sense of predictability and control, both of which are crucial for widespread adoption [27].

1.6. Streamlining Operations with Charging Slot Monitoring

As more people adopt EVs, the need for charging stations will undoubtedly grow. This spike may cause congestion, with users frequently suffering uncertainty regarding station availability [28]. Charging slot monitoring gives a real answer. By regularly tracking and updating slot occupancy, users may be notified in real-time regarding station availability. Such systems may also interface with booking services, enabling customers to schedule spaces, eliminating wait times and ensuring a smoother charging experience [29].

1.7. Prioritizing Security: The Incorporation of Radio Frequency Identification (RFID) Systems

With the development of digital infrastructure, security considerations have become crucial. Charging stations, being public utilities, are exposed to unwanted entry and possible abuse [30]. RFID (radio frequency identification) technology gives an elegant answer to this difficulty [31]. Approved automobiles are granted RFID tags; hence, the charging station can promptly verify users, guaranteeing that only those with authorization can use the charging services. This layer of security guarantees that the infrastructure is both safe and trusted by its users [32].

1.8. Literature Review

In a recent study [33], the implications of the pandemic on Croatia's EV monitoring infrastructure, specifically linked to charging data, were investigated. The study underlines the ramifications of such worldwide occurrences in terms of the stability and operation of EV charging infrastructure. Further research [34] offered a unique configuration approach for the energy storage system (ESS) in EV rapid charging stations. It Hitive approach aims to both alleviate the impact of fast charging stations on the associated distribution network and enhance their economic efficiency. In another article [35], a location model is developed for EV public charging stations, designed to optimally preserve the current activities of EV drivers by incorporating elements such as drivers' activities, charging options, range concerns, and future trip energy needs. This deterministic model is further exemplified with a coverage location approach focused on maximizing these driver activities, using Beijing, China as its practical application case study. Ref. [36] focuses on the DC micro-grid system of a PV power generation EV charging station, introducing a hybrid energy storage solution combining flywheel energy storage and battery storage. The flywheel energy storage specifically addresses high-frequency power fluctuations and caters to some low-frequency power stabilization. Similarly, in ref. [37], an advanced optimization algorithm is proposed to determine the optimal combination of control parameters for a voltage source inverter. This inverter bridges a PV power system with an EV charging station via a shared grid-connected AC bus. The salp swarm algorithm is employed to fine-tune these parameters, aiming to reduce DC bus voltage fluctuation by harmonizing active power flow and grid-injected harmonics.

Moreover, further research [38] introduces a method designed to aid electricity distribution firms in pinpointing optimal connection points for fast charging stations, to minimize expenditures on new installations and network fortifications. The study in ref. [39] introduces a day-ahead EV scheduling strategy, using the vehicle-to-grid (V2G) power transfer to control single-phase EV charging demand, thereby mitigating unbalances. This strategy also schedules EVs according to a price-based demand response program. The objective is to utilize multi-objective ordering to maximize economic benefits by modulating EV charging and discharging rates based on fluctuating electricity prices. This concurrently shifts EV power consumption among phases to diminish imbalances. The research in ref. [40] tackles the challenge of reducing the daily peak power at a charging station, considering uncertainties in vehicle arrival and departure times, as well as the required energy for charging. To evaluate the efficacy of the charging service amidst these uncertainties, a pertinent customer satisfaction policy is applied. In ref. [41], a novel methodology is proposed to determine the ideal placement of EV semi-fast charging stations at a community scale using a multi-objective approach. Past research [2] delves into the intricate interplay between the technical, financial, and environmental impacts arising from customer participation in economic growth and load management. A novel design for solar-powered EV charging stations is presented and assessed using the HOMER Grid. A case study further illuminates the potential advantages, spanning economic, technical, and energy management facets, garnered through customer energy engagement coupled with the incorporation of PV-based charging infrastructures.

The study in ref. [4] shows a comprehensive examination of methodologies for predicting the state of charge (SOC), state of health (SOH), and remaining lifespan of EV batteries. The paper further analyzes viable application techniques and real-world usage situations. A solution that encompasses online inspection and fault detection throughout the battery's life cycle is proposed. The obtained solution is further simulated using detailed SOC and SOH algorithms and specific scenario application drive methods. The research article in ref. [42] shows that there is an emphasis on the integrated scheduling of pricing and power management for EVs at charging stations. Given the unpredictability of EV arrivals, charging needs, and variable renewable power generation, the issue is modeled as a Markov decision process. Subsequently, a bi-level optimization framework is established to address the outlined stochastic programming model. In the article in ref. [6] the integration of a flywheel and PV hybrid system (FL–PVHS) in an EV workplace charging station is explored. The study delves into the optimal sizing and operational costs of this hybrid system, aiming to enhance its financial attractiveness. A comprehensive assessment of component costs is undertaken, factoring in initial investments, yearly maintenance, degradation, replacements, and the eventual residual value to ensure a grounded analysis. In ref. [7] a deep dive is taken into the challenge of optimally deploying EV charging stations on integrated transportation and power distribution networks. This deployment problem has emerged as a pivotal concern against the backdrop of the growing adoption of EVs in recent times.

Addressing gaps in current EV charging technology, this research focuses on establishing an advanced solar-based charging station with several novel contributions. The study aims to implement WPT for stationary EV charging, eliminating traditional constraints and enhancing user convenience. It introduces an automated charging system for efficient power delivery with minimal human intervention, addressing potential inconsistencies. The real-time monitoring of PV system parameters ensures a steady energy supply. On the other hand, the integration of IoT for battery charging monitoring improves transparency in the user experience. This study innovates by introducing a technique for charging slot monitoring to optimize processes and minimize congestion. Furthermore, the implementation of an RFID-based authentication system enhances charging station security, preventing unauthorized access and maintaining infrastructure integrity. The research questions revolve around the feasibility and effectiveness of these innovations, contributing to the advancement of sustainable and efficient EV charging infrastructure.

1.9. Main Contribution and Focus of the Research

The main aim of this research revolves around the establishment of an advanced solar-based charging station for EVs. Delving into this topic, several novel contributions were made:

- *Implementation of WPT for Static Charging:* This research has established the use of WPT for stationary EV charging. By eliminating the traditional restraints of plugs and cables, this study underscores the benefits and feasibility of WPT in enhancing user convenience and potentially expanding the utility of charging stations.
- *Introduction of Charging Automation:* An automated charging system has been introduced. By ensuring optimal power delivery with minimal human intervention, this automated approach paves the way for a more efficient and streamlined charging process, addressing potential inconsistencies and inefficiencies.
- *Real-time Monitoring of PV System Parameters:* This study has built a method to monitor the power parameters of the PV modules, realizing the need for a dependable power supply. This method makes it easier to monitor performance metrics in real-time, guaranteeing a steady supply of energy and spotting any inefficiencies.
- *Integration of IoT for Battery Charging Monitoring:* This research has given owners a way to obtain real-time information on their vehicle's charging state by integrating IoT capabilities into the charging system. This is a major improvement in terms of increasing transparency and strengthening the EV charging user experience.
- *Introduction of Charging Slot Monitoring:* An innovative technique for monitoring charging slots has been created to tackle the possible problem of charging station congestion. By minimizing lengthy wait periods and optimizing the charging process overall, this function guarantees the effective use and administration of many charging stations.
- *Implementation of RFID-based Charging Station Security:* This study implemented an RFID-based authentication system to guarantee the security and safety of the charging stations. By firmly preventing unwanted access to the charging infrastructure, this precaution maintains infrastructure integrity and user confidence.

2. Problem Formulation

2.1. Implementation of Wireless Power Transfer (WPT) for Static Charging

The proposed research focuses on the parameters involved in Wireless Power Transfer (WPT) for static charging. The key variables include the total transmitted power (P_t), power received at the vehicle coil (P_r), self-inductances of source and receiver coils (L_s and L_r), mutual inductance between coils (M), frequency (f), and coupling coefficient (k). The objective is to optimize the coupling coefficient (k) and ensure that the frequency (f) closely matches the resonant frequency (f_0) to maximize the efficiency of the wireless power transfer system.

$$k = \frac{M}{\sqrt{L_s L_r}} \tag{1}$$

The resonant frequency, f_0, is the following:

$$f_0 = \frac{1}{2\pi\sqrt{L_s C_s}} \tag{2}$$

where C_s is the capacitance at the source.

Objective: Optimize k and ensure f is close to f_0 to maximize efficiency.

2.2. Introduction of Charging Automation

The study introduces the concept of charging automation, considering the total energy required by the vehicle (E_v) and the energy charged over time (E_c(t)). The charging current (I(t)) is modeled through a differential equation that involves the battery voltage (V). The objective is to solve this differential equation to achieve efficient charging without overshooting the total energy requirement (E_v).

The charging differential equation can be expressed as follows:

$$\frac{dE_c(t)}{dt} = V \times I(t) \tag{3}$$

where V is the battery voltage.

Objective: Solve the differential equation to ensure efficient charging without overshooting E_v.

2.3. Real-Time Monitoring of PV System Parameters

The proposed research also addresses the real-time monitoring of parameters in a PV system, including power from PV modules (P_{pv}(t)), PV current (I_{pv}), and PV voltage (V_{pv}). The power balance equation is presented to guide the adjustment of system impedance to maximize power output under varying sunlight conditions.

Power balance is given by the following:

$$P_{pv}(t) = V_{pv} \times I_{pv} \tag{4}$$

Objective: Adjust the impedance of the connected systems to maximize $P_{pv}(t)$ for varying sunlight conditions.

2.4. Integration of IoT for Battery Charging Monitoring

The study's focus is on integrating the IoT for monitoring battery charging. The SoC (S(t)) is modeled, and the rate of change of SoC is expressed in terms of time. The objective is to integrate this rate of change over time to predict the full charging time and provide real-time feedback on the battery charging process. The rate of change of SoC is given by the following:

$$\frac{dS(t)}{dt} = \frac{I(t)}{C} \tag{5}$$

where C is the battery capacity.

Objective: Integrate the rate of change over time to predict full charging time and provide real-time feedback.

2.5. Introduction of Charging Slot Monitoring

This research introduces queuing theory to address the monitoring of charging slots. Total slots (N_t), arrival rate of vehicles (λ), and departure rate of vehicles (μ) are considered. The probability (P_0) that there are no cars in the system is calculated. The objective is to maintain a balance between the arrival and departure rates to ensure the efficient utilization of charging slots.

$$P_0 = \left(\sum_{k=0}^{N_t - 1} \frac{(\lambda/\mu)^k}{k!} \right)^{-1} \tag{6}$$

Objective: Maintain a balance between λ and μ to ensure the efficient utilization of charging slots.

2.6. Implementation of RFID-Based Charging Station Security

Finally, the paper deals with the implementation of security measures using radio-frequency identification (RFID) for charging stations. Total user requests (U) and authenticated requests (U_a) are considered, and the security efficiency (η_s) is defined using probability and total monitoring time (T). The objective is to implement security measures to ensure that the security efficiency approaches 1, thereby providing a highly secure charging system:

$$\eta_s = \frac{\int_0^T U_a dt}{\int_0^T U dt} \tag{7}$$

where T is the total monitoring time.

Objective: Implement security measures to ensure η_s approaches 1 to provide a highly secure system.

3. Methodology

3.1. Design and Implementation of WPT with Charging Automation

To achieve the integration of WPT with charging automation, this study focused on key components designed for optimal efficiency and precision (Figure 1). The central element of this implementation is the utilization of copper coils specifically designed for EV charging. These coils, chosen for their proven efficiency in wireless energy transmission, form the backbone of the charging infrastructure. The charging automation process is composed by strategically deploying IR sensors within parking slots. These sensors play a pivotal role in swiftly detecting the presence of an EV upon arrival and parking. This instantaneous detection mechanism serves as the trigger for initiating the WPT process. The integration of sensors is organized in such a way that form a crucial link to a dedicated controller. The controller, intricately connected to the detection sensors, takes charge of managing the power flow during the entire charging process. The automation system, therefore, operates cohesively with a cooperation between the robust copper coils, sensors, and the controlling unit. This interaction ensures not only the efficient use of energy and its wireless transmission to parked EVs but also the automation of the charging process. By intricately weaving together the proven robustness of copper coils with the precision of sensors and controllers, the methodology establishes an automated, efficient, and user-friendly charging experience for EVs. The step by step procedure of the proposed system is explained in Figure 2.

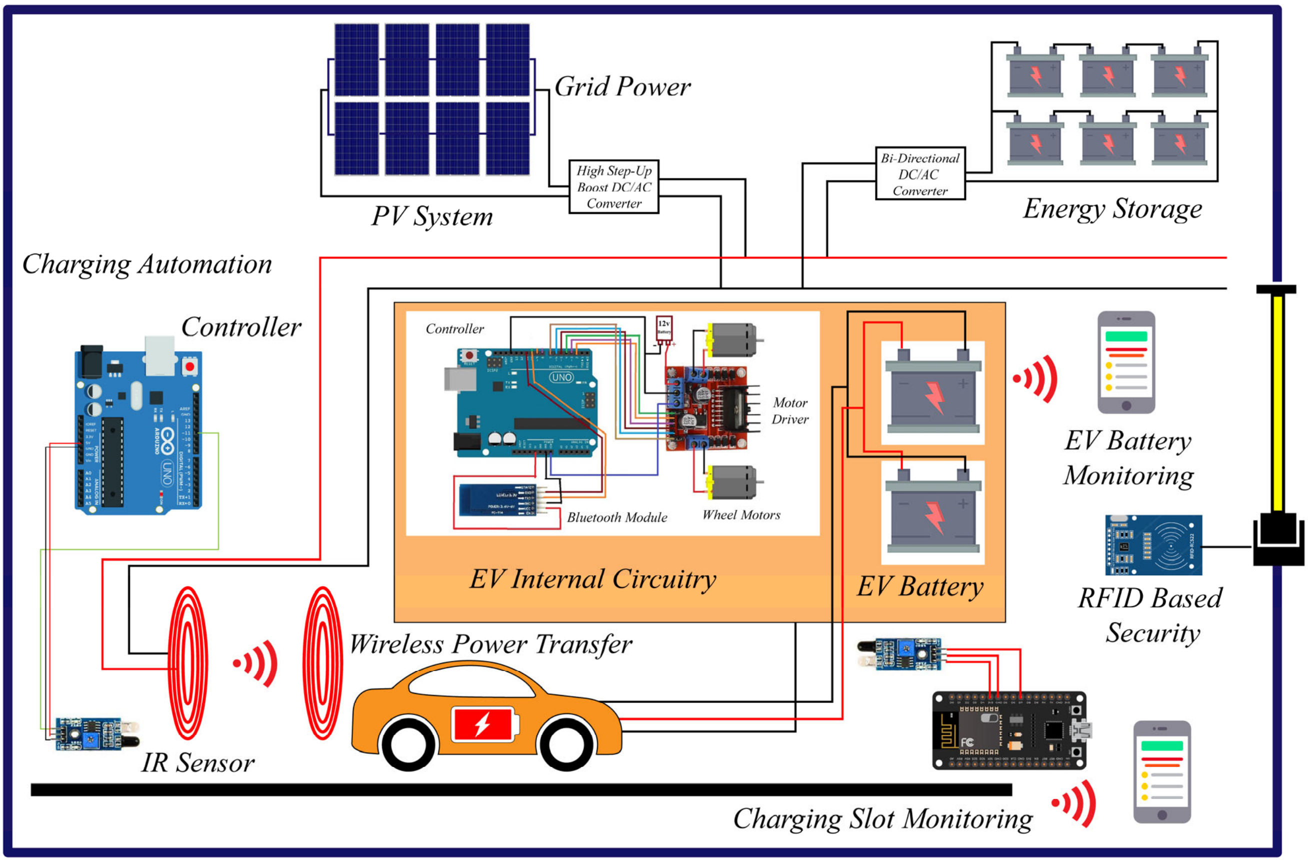

Figure 1. Integration of renewable energy and IoT for advanced wireless power transfer in EVs.

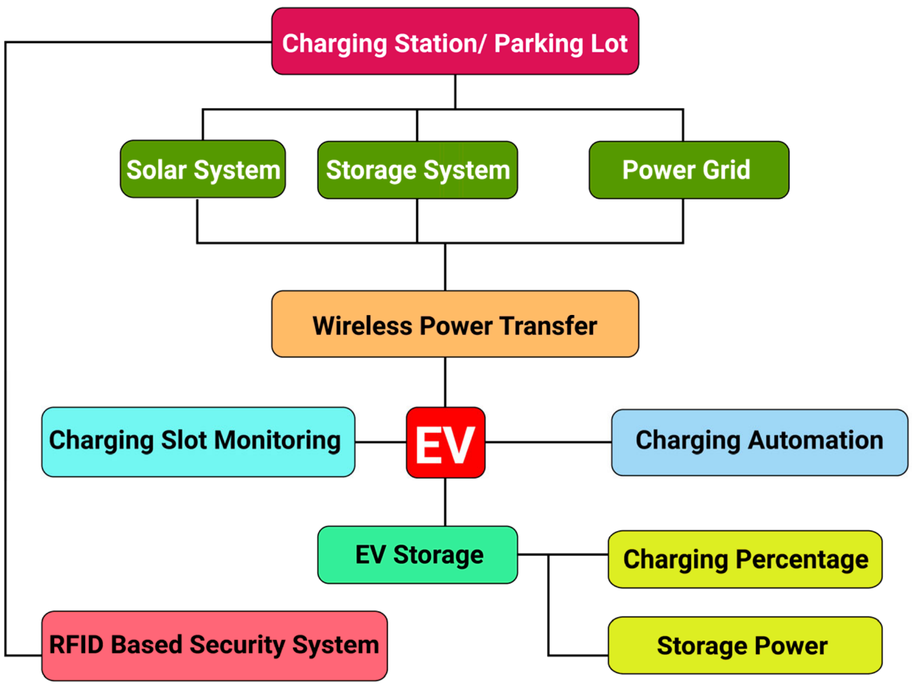

Figure 2. Flowchart of the proposed system.

3.2. Monitoring System for PV Modules

With the primary energy source being solar input, a monitoring system is required for its effective use (Figure 3). The methodology integrates current and voltage sensors with the PV module system, with a focus on precision and real-time data provision.

Specifically selecting ACS712 current sensors and 0–25 V DC voltage sensors, the system operates at high frequency for the continuous monitoring of PV modules' electrical properties. The study employs ACS712 and 0–25 V DC voltage sensors with the ESP32 microcontroller and Blynk IoT platform to monitor and analyze the power parameters of the PV system. The ACS712 sensors offer accurate current measurements, complemented by precise voltage readings from the 0–25 V DC sensors. The ESP32 microcontroller serves as the central processing unit, ensuring real-time data acquisition, while the Blynk IoT platform acts as the interface for remote monitoring and visualization. This integrated hardware and IoT setup enhances the efficiency and accessibility of monitoring the solar energy system's performance.

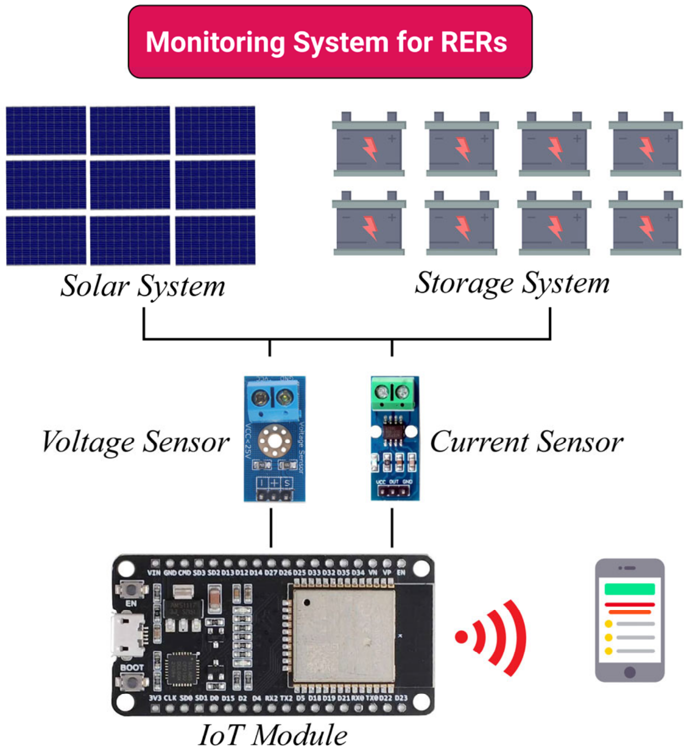

Figure 3. Monitoring system for PV modules.

3.3. Incorporation of IoT for Battery Charging Monitoring

This study employs IoT capabilities to establish an efficient battery monitoring system (see Figure 4). The system recognizes the increasing demand for real-time charging information and remote accessibility. Initial steps involved a thorough analysis of the potential and challenges associated with IoT-based solutions. A pivotal element in the methodology was the integration of the widely used IoT analytics platform, "ThingSpeak". The subsequent stage focused on connecting the battery system to the relevant IoT module, ACS712 current sensor, and 0–25 V DC voltage sensor. This integration ensured the accurate recording of battery power and charge percentage data. Calibration processes were implemented to guarantee precise readings from these sensors, emphasizing data consistency and dependability. Following the collection of sensor data, the ThingSpeak program processed the information and presented it on the platform in a user-friendly format. This cloud-based approach facilitates remote access, allowing users to monitor their battery's power value, charge percentage, and charge level from any location. The methodology aimed to deliver a comprehensive battery monitoring system by incorporating the analytical capabilities of ThingSpeak with the functionalities of IoT sensors. This placed a specific emphasis on remote access and real-time updates for users.

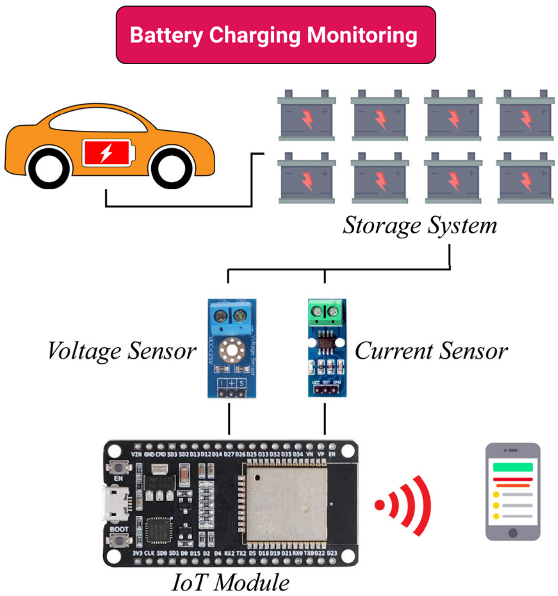

Figure 4. Incorporation of IoT for battery charging monitoring.

3.4. Charging Slot Monitoring System

To monitor charging slots, the proposed study also makes use of the IoT's capabilities. Acknowledging the increasing need for dynamic, real-time data about EV charging infrastructure, the technique began with a thorough investigation of possible IoT devices fit for this use case. Infrared (IR) sensor integration forms the basis of the monitoring system. The selection of this sensor stemmed from its accuracy and capacity to ascertain the charging slot occupancy state. When the IR sensor notices a change in its surroundings that may be the result of a parked car, it transmits the pertinent information to the linked IoT module.

We integrated the Blynk application for data visualization and user engagement. Blynk, which is renowned for its user-friendly interface and real-time data processing, gives consumers access to real-time slot occupancy updates. The Blynk application receives the data from the IR sensor and channels it via the IoT module to show it in an understandable manner. The system's calibration and setup were very important. Crucial phases in the process included making sure that the IR sensors functioned correctly and that the IoT module transferred these data to the Blynk application without any problems (Figure 5).

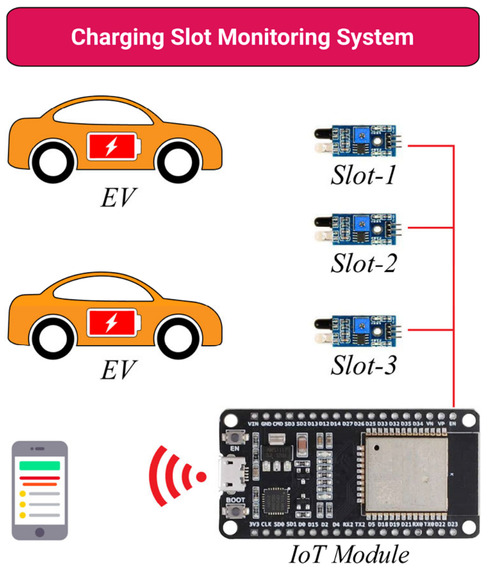

Figure 5. Charging slot monitoring system.

3.5. RFID-Based Charging Station Security

Using RFID technology, a structured research strategy was used to develop a safe environment for EV charging stations. The main goal was to improve the charging facility's usability and safety by limiting access to only authorized customers. To identify and validate certain RFID tags linked to authorized users, the technique started with the selection and integration of a suitable RFID module. To guarantee optimal operation, this module's performance, sensitivity, and dependability underwent extensive testing under a variety of scenarios, given its relevance.

A servo motor that controls the entry gate's functioning is connected to the RFID module. The module alerts the servo motor to open the gate and provide entry when it detects an authorized RFID tag. On the other hand, if there is no authorized tag or any inconsistency, the gate stays locked and prevents entry. A microcontroller is a crucial part of this integrated system's administration and coordination. This component's programming handled possible circumstances such as multiple simultaneous RFID readings or unrecognized tags, as well as processing the signals from the RFID module and controlling the servo motor's motions. Important steps in the process were selecting the microcontroller, programming it, and connecting it to the servo motor and RFID module. The goal of the study was to create a reliable and secure system that ensures that the charging station is only available to individuals with recognized credentials, thus enhancing its safety and integrity via the smooth interaction of the RFID module, servo motor, and microcontroller.

The research methodology systematically integrated WPT with charging automation for EVs. Employing copper coils for efficient energy transmission, parking slot sensors, and controllers enabled automated charging initiation upon EV arrival. The PV module monitoring system incorporated current and voltage sensors for real-time data, validated through calibration, facilitating prompt anomaly detection and optimization. IoT capabilities were used for battery charging monitoring, by integrating ThingSpeak for real-time processing and remote user access. Charging slot monitoring utilized IoT with infrared sensors, coupled with the Blynk application for user-friendly data visualization. The RFID-based charging station security strategy aimed to enhance usability and safety by restricting access to authorized users. This study integrates RFID modules with a servo motor and microcontroller for reliable system operation. The methodology used integrated various technologies, which ensured an efficient, automated, and secure charging experience for EVs (Figures 1 and 2).

4. Result and Discussion Section

4.1. Prototype for WPT for Static Charging with the Integrated RERs

This research led to the development of a prototype for WPT geared toward static charging that seamlessly integrates RERs. The design uses a combination of a solar energy system and a battery energy storage mechanism which, when paired with a charge controller, shows promising potential in sustainable EV charging. This PV system is designed specifically to fuel the WPT process to EVs. Two coils underline the core functionality of the WPT, i.e., a transmitting coil and a receiving coil. The transmitting coil wirelessly forwards power, which the EV, equipped with the receiving coil, accordingly harnesses. Notably, the proposed model integrated a Bluetooth-controlled robot that mimics the role of an EV, adding a layer of modern automation to the prototype. Additionally, an innovative feature of our prototype is the incorporation of charging automation. This ensures that the entire charging process is not only wireless but also largely autonomous, pushing the boundaries of conventional EV charging (Figure 6).

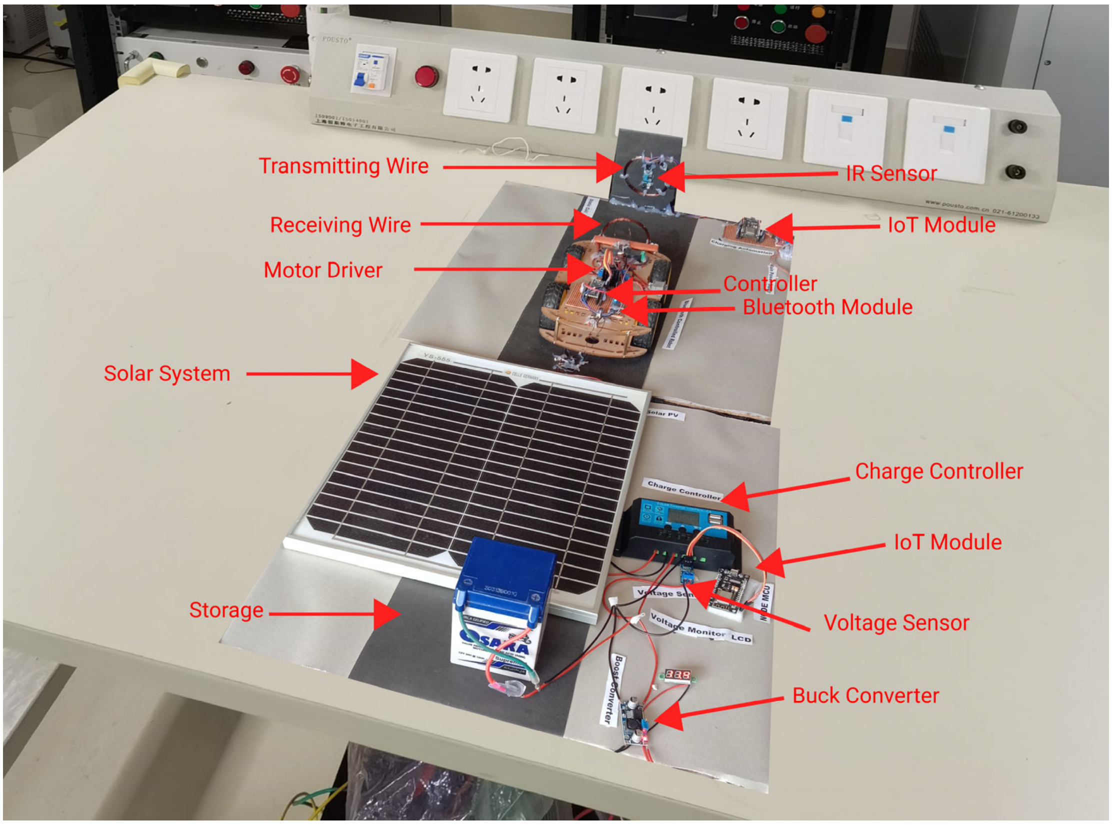

Figure 6. Prototype for WPT for static charging with the integrated RERs.

4.2. WPT and IoT-Based Charging Automation

To develop an enhanced charging automation system, this study goes further into the integration of WPT with the emerging field of the IoT (Figure 7). The suggested concept is a major advancement over traditional wireless charging techniques. With this improved setup, the IoT sensors recognize the presence of an EV parked in the assigned parking area and automatically start the charging process without any human intervention. The EV receives electricity automatically via the use of WPT, starting a smooth charging cycle. Thus, charging is made easier and more efficient since the car starts charging as soon as it is parked. This kind of automation highlights the possibilities for integrating energy systems with smart technology, pointing to a day when charging a car may be as simple as parking.

While the developed prototype for WPT and its integration with RERs highlight promising potential in sustainable EV charging, several challenges and limitations should be considered for real-world scenarios. The integration of WPT with RERs introduces uncertainties related to varying environmental conditions, such as inconsistent sunlight for solar energy. The robustness of the charging automation system, which is reliant on IoT sensors, may face challenges in accurately detecting and initiating charging for all EVs, especially in densely populated or dynamically changing parking environments. Additionally, the practical implications and scalability of the proposed model, including the incorporation of charging automation, need thorough exploration to ensure its effectiveness and viability in diverse settings. These considerations highlight the importance of addressing challenges and uncertainties for the successful implementation of WPT systems in real-world applications.

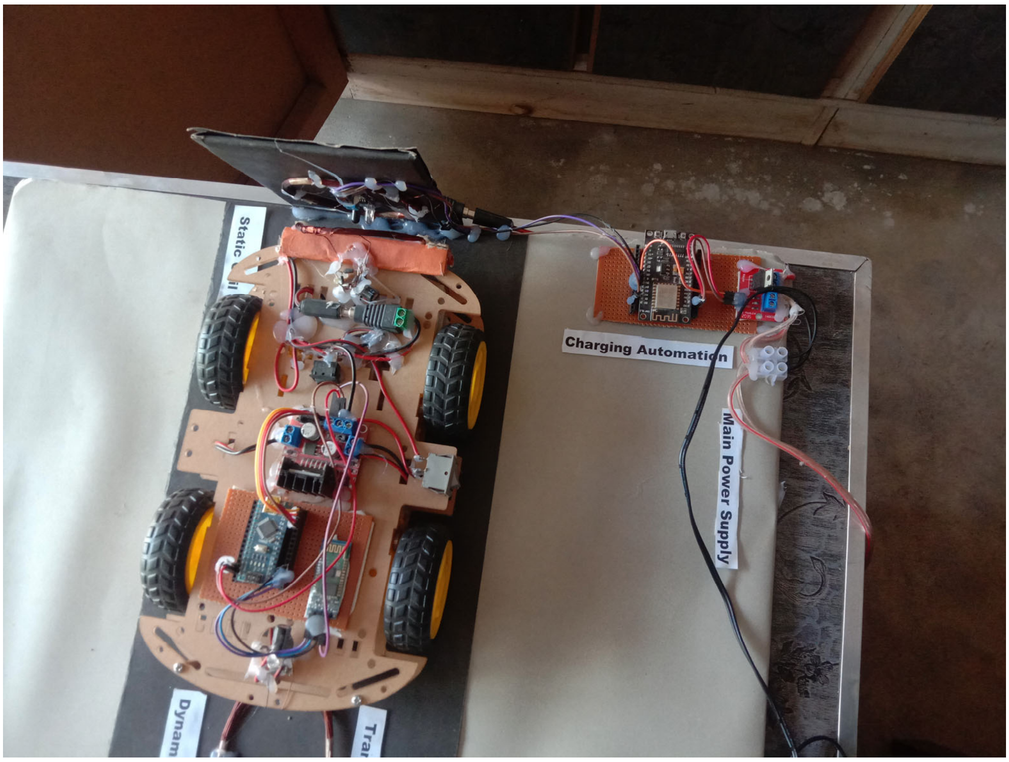

Figure 7. WPT and IoT-based charging automation.

4.3. IoT-Based Power Parameters Monitoring of EVs Battery and PV System

This study offered a prototype that focuses on leveraging the IoT technologies to monitor the power characteristics of the PV system and the battery energy storage system (BESS). The Blynk program is an essential component of the monitoring process (Figures 8 and 9). It is a powerful tool used to observe several vital power indicators in real-time. The Blynk application effectively monitors the PV system's power generation, energy consumption, current, and voltage parameters, providing users with a thorough understanding of its operational state and efficiency, according to the detailed findings. Moreover, the study broadens its scope to include the careful observation of EV batteries. Metrics such as the current energy reserve and the percentage of charge are among the detailed battery power statistics that the system offers. With the support of this Internet of Things infrastructure, consumers can easily keep an eye on their EVs' charging status from a distance. Incorporating these monitoring tools improves user awareness while also making it easier to manage and optimize power consumption and storage in the complex tango between PV systems and EVs.

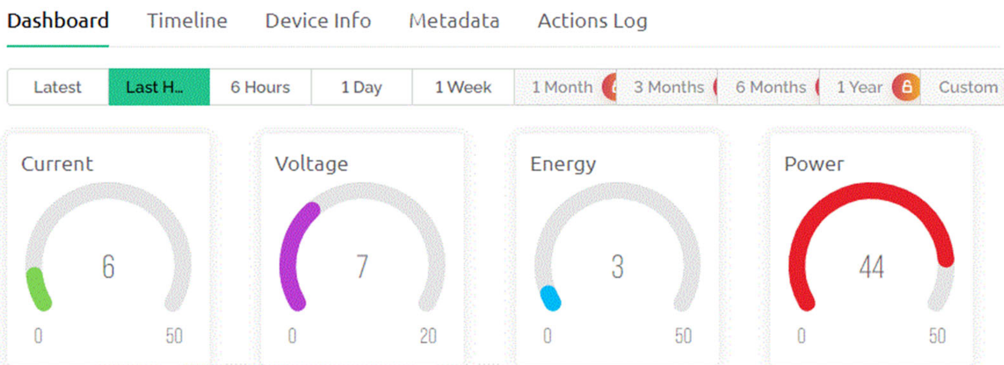

Figure 8. IoT-based power parameters monitoring of PV system.

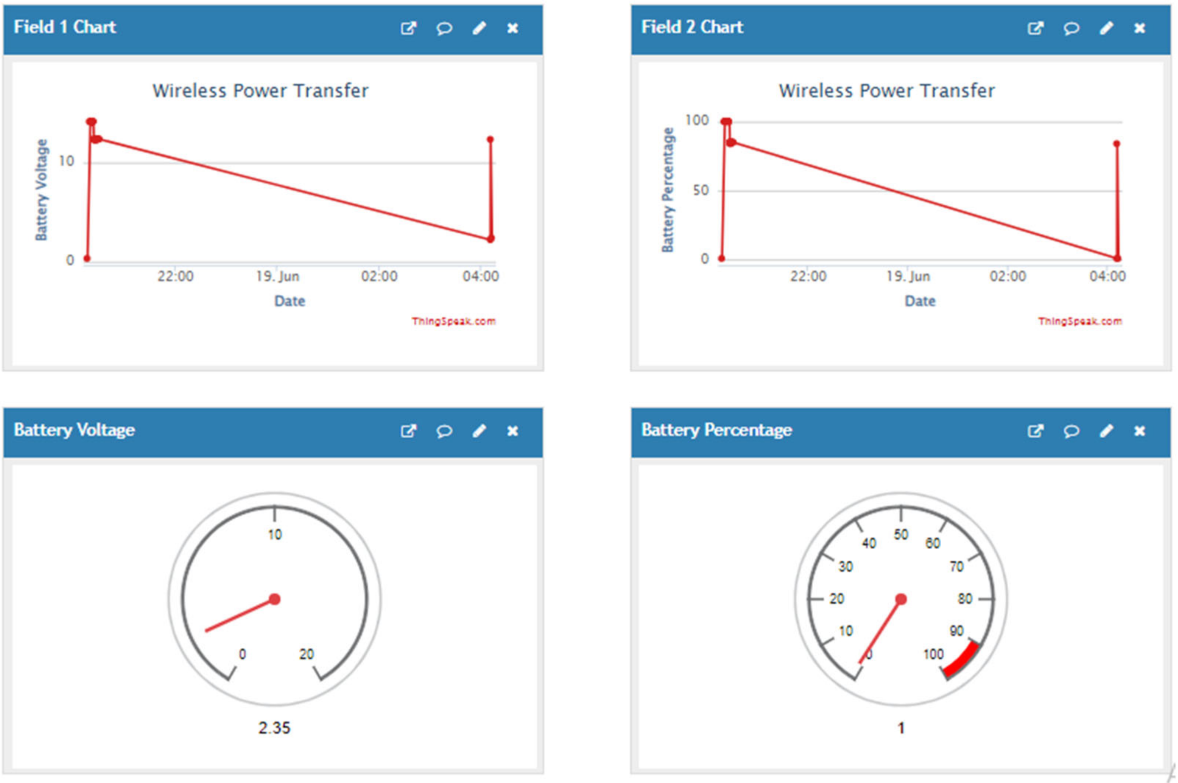

Figure 9. IoT-based power parameters monitoring of EVs battery.

4.4. Charging Slot Monitoring and RFID-Based Security System

The suggested study presented a novel approach to improving the security and administration of EV charging stations by fusing RFID and IoT technologies. The main component of the suggested system is an Internet of Things module-powered charging slot monitoring mechanism. The IoT-enabled site immediately changes the charging slot status, showing whether it is occupied or available when an EV is parked in a specified slot. The Blynk IoT application, a state-of-the-art instrument created especially for slot monitoring in this situation, facilitates real-time data monitoring (Figures 10 and 11).

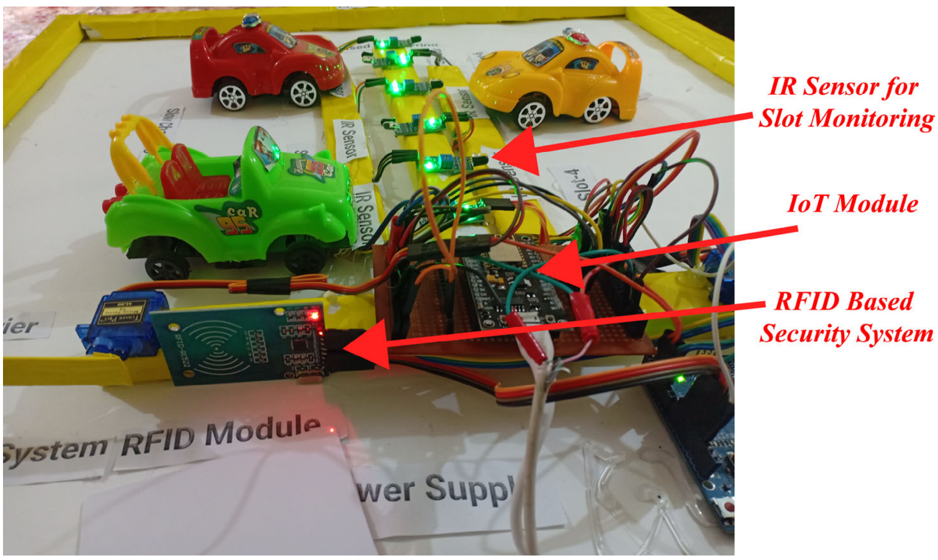

Figure 10. Charging slot monitoring and RFID-based security system.

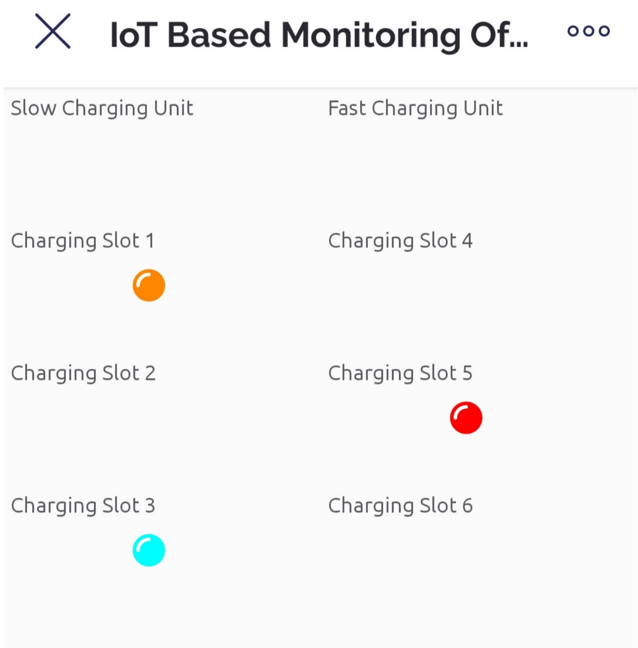

Figure 11. Charging slot monitoring.

Even with the benefits associated with slot monitoring, security is still the priority. To tackle this issue, the suggested solution incorporates an RFID-driven security function that guarantees exclusive access to the charging stations for authorized users only. Users must scan a specific RFID card when accessing the charging station. After verifying the user's credentials, the system only allows access to those who with permission. This dual-layered strategy offers a future where EV charging is both safe and easy by fusing the effectiveness of IoT-based slot monitoring with the security of RFID identification.

4.5. Case Study: PV and BESS Integrated in Grid Office Charging

In the proposed case study of a grid office charging station, the integrated BESS and PV systems are designed to enhance energy sustainability and efficiency. The PV system features a generic flat plate with a capacity of 200 kW, capturing solar energy to contribute to the station's power needs. To store and manage the generated energy, the system incorporates 30 strings of Tesla Powerwall 2.0, providing reliable and scalable storage solutions. The system converter, with a capacity of 118 kW, plays a crucial role in converting and managing the flow of energy between the PV system, storage, and the grid. The grid itself, with a substantial capacity, serves as both a source of power and a backup during periods of high demand or low solar generation. This integrated approach reflects a comprehensive and advanced solution for a sustainable and resilient grid office charging station.

4.5.1. Financial Overview of Proposed Energy System

Table 1 and Figure 12 provide a comprehensive overview of the financial aspects associated with the components of the proposed energy system. The "Generic flat plate PV" incurs a capital cost of USD 70,000, with an additional operating cost of USD 51.71. Notably, there are no replacement or salvage costs associated with this photovoltaic resource. The "Grid" component requires a substantial operating cost of USD 1.02 million, reflecting its significant role in providing power to the system. The "System Converter" has a capital cost of USD 35,359 and incurs a replacement cost of USD 15,002. Interestingly, it shows a negative salvage value of USD −2824, possibly indicating a potential resale or repurposing value. The "Tesla Powerwall 2.0" involves a higher capital cost of USD 195,000, with operating costs amounting to USD 38,783. Replacement and salvage costs are also significant at USD 172,270 and USD −23,357, respectively. As a whole, the integrated

"System" requires a total capital investment of USD 300,359 and operating costs of USD 1.06 million. Replacement and salvage costs contribute to a total of USD 187,272 and USD −26,180, respectively. The comprehensive analysis of these financial metrics provides a holistic understanding of the economic implications of each component within the proposed energy system.

Table 1. NPC of the proposed grid PV and BESS-based office charging (amounts given in USD ($)).

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic flat plate PV	$70,000	$51.71	$0.00	$0.00	$0.00	$70,052
Grid	$0.00	$1.02 M	$0.00	$0.00	$0.00	$1.02 M
System Converter	$35,359	$0.00	$15,002	−$2824	$0.00	$47,538
Tesla Powerwall 2.0	$195,000	$38,783	$172,270	−$23,357	$0.00	$382,696
System	$300,359	$1.06 M	$187,272	−$26,180	$0.00	$1.52 M

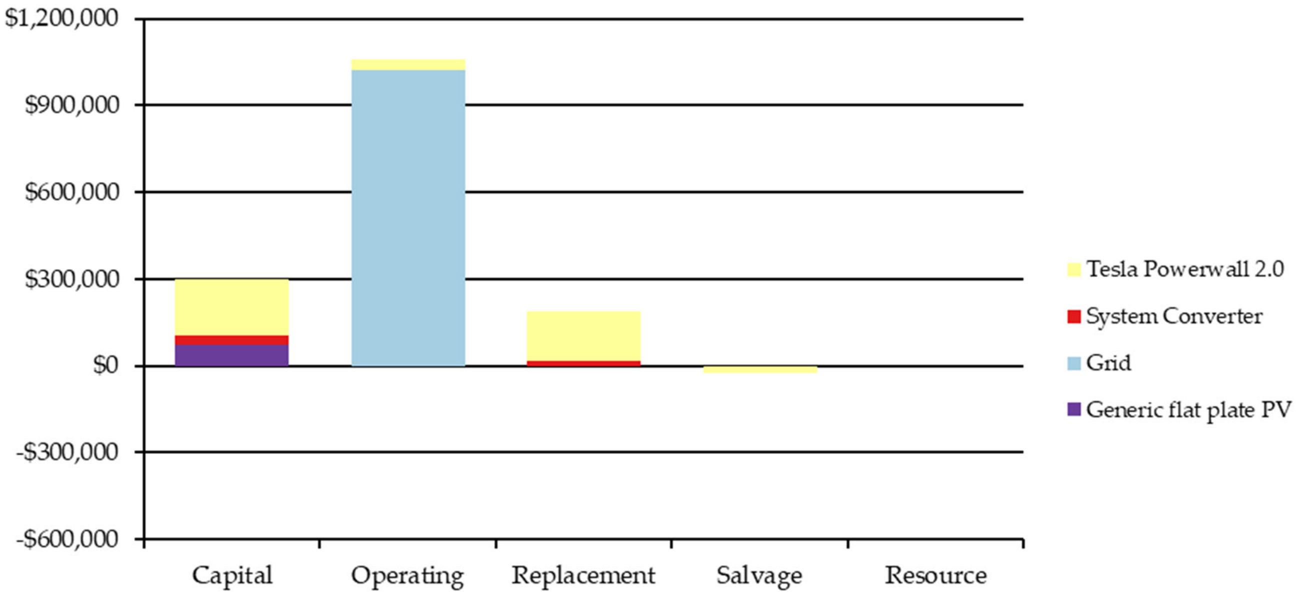

Figure 12. Financial overview of proposed energy system components (amounts given in USD ($)).

4.5.2. Annualized Power Production and Consumption of Proposed Energy System

Table 2 and Figure 13 delineate the power production breakdown in kWh and percentage distribution between two primary sources within the energy system. The "Generic flat plate PV" component contributes significantly, generating 360,102 kWh, constituting 56.7% of the total power output. In contrast, "Grid Purchases" account for 275,247 kWh, representing 43.3% of the overall power production. The cumulative result reflects a total power production of 635,349 kWh, providing a clear understanding of the proportional contribution of each source to the energy system's overall output.

Table 2. Power production distribution.

Power Production	kWh/year	Percentage
Generic flat plate PV	360,102	56.7
Grid Purchases	275,247	43.3
Total	635,349	100

The power consumption profile for the system is outlined in Table 3. The "AC Primary Load" dominates with a substantial consumption of 598,965 kWh/year, accounting for 97.7% of the total power usage. In contrast, "Grid Sales" contribute 14,092 kWh/year, constituting 2.30% of the overall consumption. The comprehensive data indicate a clear hierarchy in power utilization, emphasizing the significant role of the AC Primary Load in the system's energy consumption, with minimal reliance on grid sales. The total power consumption amounts to 613,057 kWh/year, providing a quick overview of the distribution between internal load and grid sales.

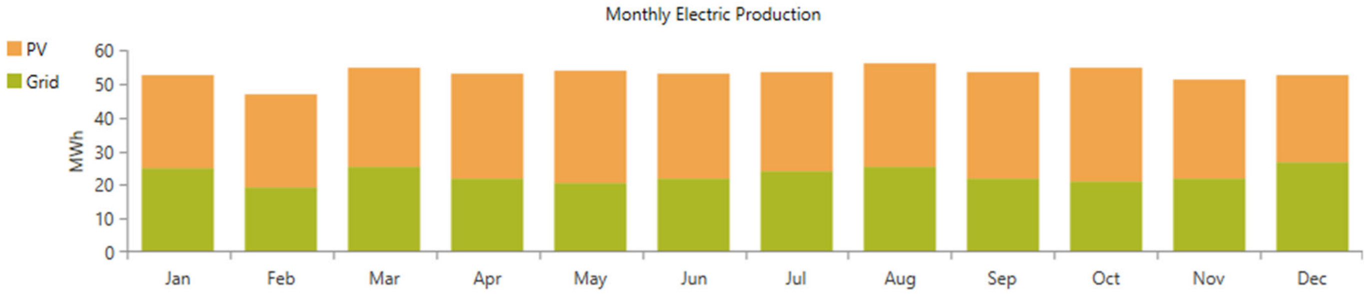

Figure 13. Annualized power sharing dynamics between PV and grid.

Table 3. Annualized power consumption.

Power Consumption	kWh/year	Percentage
AC Primary Load	598,965	97.7
Grid Sales	14,092	2.30
Total	613,057	100

4.5.3. Performance Analysis of BESS and PV System

The BESS outlined in Table 4 is characterized by a robust configuration and performance metrics. It consists of 30 Tesla Powerwall 2.0 batteries, each forming a string, with all 30 strings connected in parallel. This setup provides an autonomy of 5.79 h, signifying the system's capability to sustain power independently for this duration. The nominal and usable capacity of the system is a significant 396 kWh, indicating a high level of efficiency in energy storage and utilization. In terms of cost and longevity, the storage wear cost is estimated at USD 0.102 per kWh, a figure that reflects the cost implications of battery wear over time. Over its expected 10 year lifespan, the BESS is projected to have a lifetime throughput (the total energy it can process) of 315,880 kWh. Annually, the system is expected to receive 33,063 kWh of energy, while it outputs 29,800 kWh, highlighting a relatively high efficiency with a loss of 3659 kWh per year. This loss can be attributed to various factors, including system inefficiencies or natural discharge. The annual throughput, which is the total energy cycled through the system each year, is calculated at 31,588 kWh. These figures collectively provide a comprehensive insight into the operational capacity and efficiency of the BESS, underlining its potential as a reliable and effective component in the office charging station setup.

Table 4. Specifications and performance metrics of the Tesla Powerwall 2.0 BESS in the office charging station setup.

Value	Quantity	Units
Batteries	30.0	qty.
String Size	1.00	batteries
Strings in Parallel	30.0	strings
Autonomy	5.79	h
Storage Wear Cost	0.102	USD/kWh
Nominal Capacity	396	kWh
Usable Nominal Capacity	396	kWh
Lifetime Throughput	315,880	kWh
Expected Life	10.0	year

Table 4. *Cont.*

Value	Quantity	Units
Autonomy	5.79	h
Storage Wear Cost	0.102	USD/kWh
Nominal Capacity	396	kWh
Lifetime Throughput	315,880	kWh
Expected Life	10.0	year
Average Energy Cost	0	USD/kWh
Energy In	33,063	kWh/year
Energy Out	29,800	kWh/year
Storage Depletion	396	kWh/year
Losses	3659	kWh/year
Annual Throughput	31,588	kWh/year

Table 5 summarizes the major performance metrics for the office charging station setup's solar PV system. The system has an average output of 41.1 kW and an average daily production of 987 kWh, with a rated capacity of 200 kW. With a capacity factor of 20.6%, the system is efficient in turning sunlight into electrical power. With an astounding 360,102 kWh produced in a year, the system demonstrates its dependability in supplying energy needs. The PV system can adjust to different solar circumstances, owing to its operating range of 0 kW to a maximum output of 197 kW. At 60.1% PV penetration, the system runs for 4352 h a year. With a levelized cost of USD 0.0150 per kWh, which indicates the system's lifetime cost per unit of energy produced, the solar PV setup is very viable economically.

Table 5. Performance metrics of the solar PV system in the office charging station.

Value	Quantity	Units
Rated Capacity	200	kW
Mean Output	41.1	kW
Mean Output	987	kWh/d
Capacity Factor	20.6	%
Total Production	360,102	kWh/year
Minimum Output	0	kW
Maximum Output	197	kW
PV Penetration	60.1	%
Hours of Operation	4352	h/year
Levelized Cost	0.0150	USD/kWh

4.5.4. Monthly Energy Transactions and Charges at the Office Charging Station

A thorough monthly and yearly summary of the energy transactions and related expenses at the workplace charging station is provided in Table 6. The station used 275,247 kWh of grid power in total throughout the year. It only succeeded in selling back a lesser quantity, amounting to 14,092 kWh, in comparison. During the year, the difference between the quantity of energy sold and the amount bought, or net energy purchased, was 261,155 kWh. A cumulative yearly energy charge of USD 79,051 is included in the related expenditures for this net energy use. The monthly variations in energy consumption and sales, which are indicative of changing operating needs or the generation of renewable energy, are shown in the table below. As an example, the month with the greatest net energy purchase was December which, at 26,280 kWh, saw the highest energy charge of USD 7909, while February was the month with the lowest at 18,956 kWh and saw the lowest energy charge of USD 5704. Given the station's dependence on grid electricity and the financial consequences of its energy management plan, this thorough analysis offers insightful information about its energy usage trends.

Table 6. Monthly energy transactions and charges at the office charging station. Details of energy purchased, sold, net purchased, and associated costs (amounts are given in USD ($)).

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Energy Charge
January	25,177	902	24,275	$7327
February	19,293	338	18,956	$5704
March	25,453	819	24,634	$7431
April	21,713	1457	20,257	$6150
May	20,761	1859	18,902	$5764
June	21,957	1576	20,382	$6193
July	23,894	1345	22,550	$6832
August	25,428	1362	24,066	$7288
September	21,844	1504	20,340	$6177
October	21,117	1721	19,396	$5905
November	21,817	699	21,118	$6370
December	26,791	511	26,280	$7909
Annual	275,247	14,092	261,155	$79,051

4.5.5. Analysis of Monthly Solar Power, BESS Performance and Grid Dynamics

The provided Figures 14–17 offer detailed insights into the functioning of a solar power system over different months, specifically January, April, July, and October. These figures track hourly variations in several key metrics: Battery SoC, PV power output, grid purchase, grid sale, and total load. The data for January show a dormant period for the battery SoC from 1 A.M. to 7 A.M., maintaining 0%. Starting at 8 A.M., there is a gradual increase, reaching a peak of 27.6% by 2 P.M., which then declines to 1.34% by 5 P.M. This trend indicates the battery's role in storing solar energy during daylight and discharging it later. PV power output is non-existent during the night hours, commencing at 8 A.M. and hitting its highest point of 165.52 kW at noon, which corresponds with peak solar activity. This output diminishes to zero by 7 P.M. The grid purchase is significant between 9 A.M. and 7 P.M., with the maximum demand of 125.23 kW occurring at 6 P.M. This highlights the reliance on grid power during times of insufficient solar generation. Interestingly, grid sales are consistently zero, suggesting that no excess energy is fed back into the grid. The total load mirrors the pattern of solar generation and grid purchase, peaking at 206.30 kW around noon and falling to zero by 8 P.M.

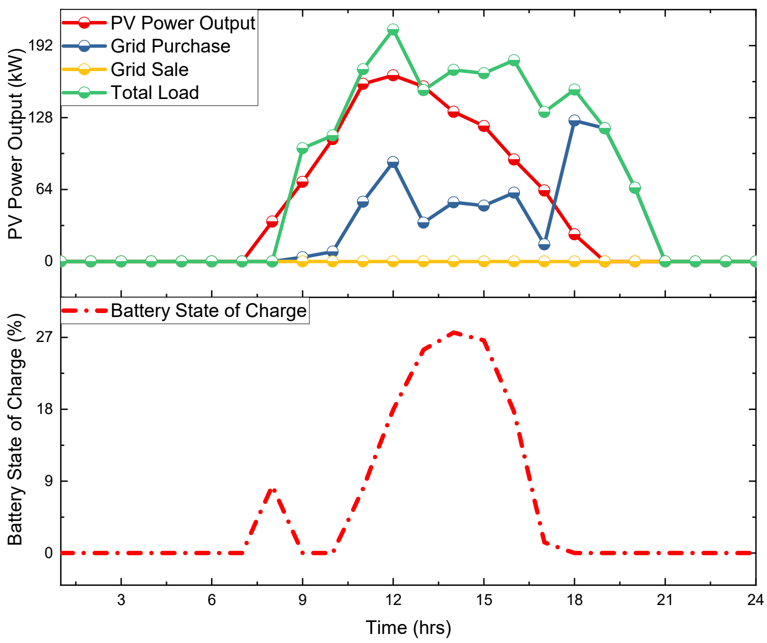

Figure 14. Monthly solar power, BESS performance, and grid dynamics in January.

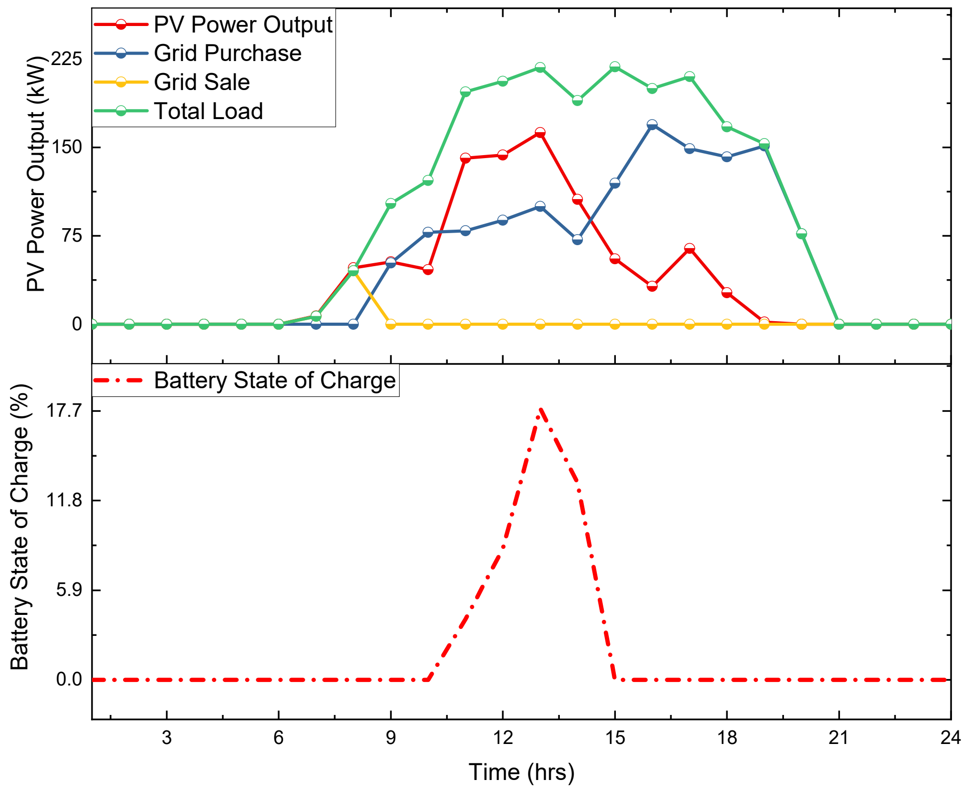

Figure 15. Monthly solar power, BESS performance, and grid dynamics in April.

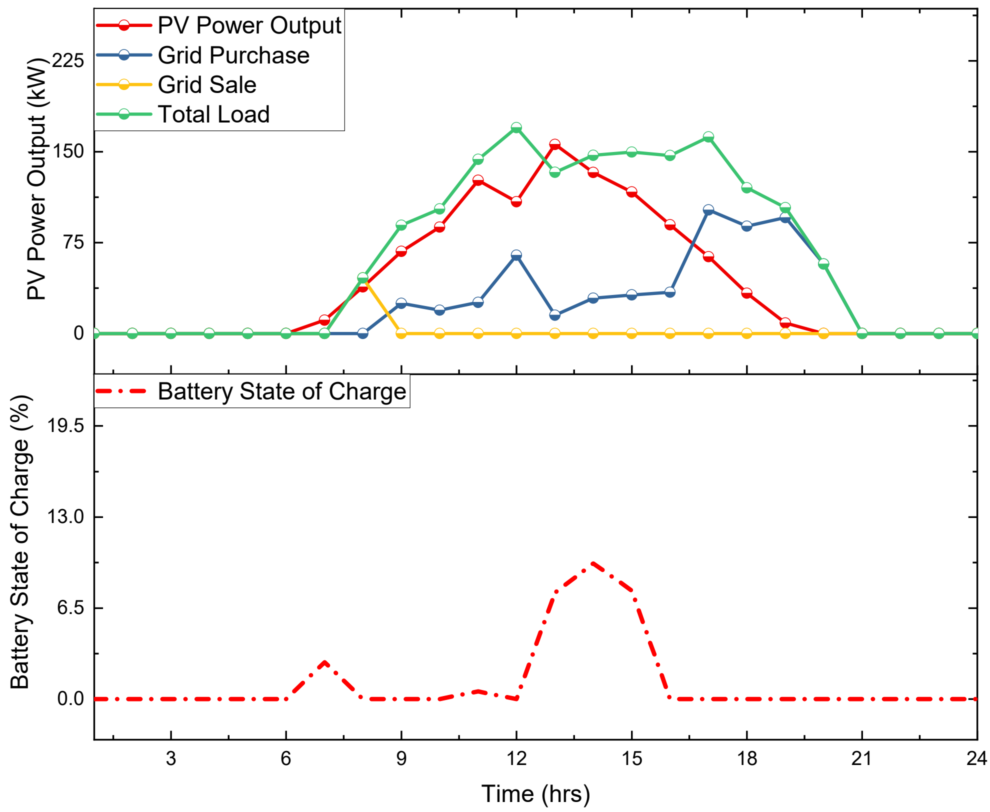

Figure 16. Monthly solar power, BESS performance, and grid dynamics in July.

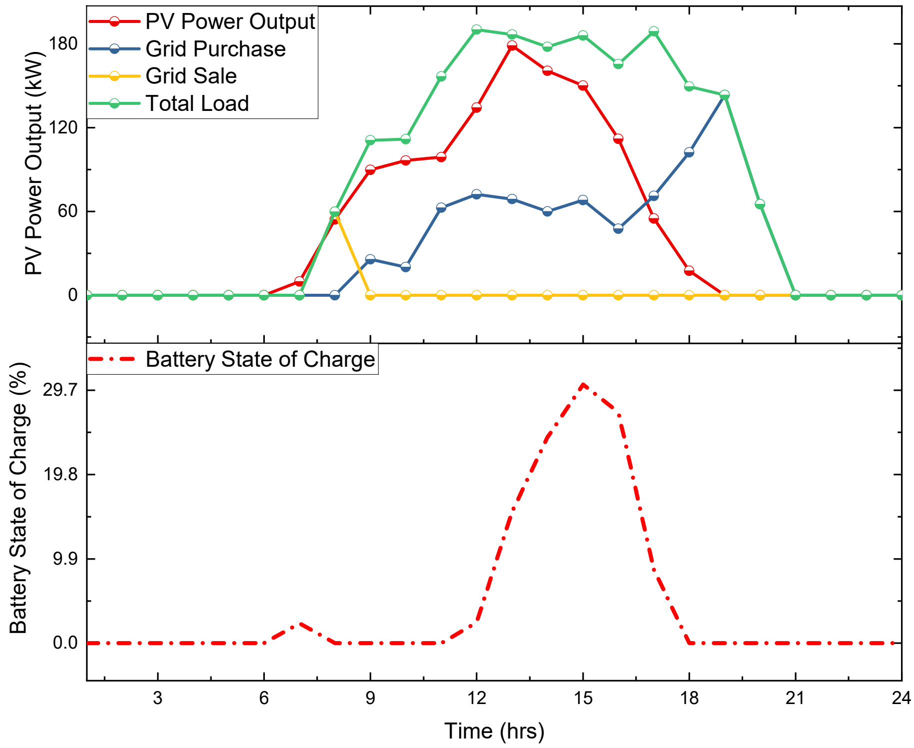

Figure 17. Monthly solar power, BESS performance, and grid dynamics in October.

In April, the battery state of charge shows minimal values throughout the month, indicating a limited role of battery storage during this period. PV power output begins at 7 A.M. and reaches its zenith at 162.63 kW by 1 P.M. It demonstrates effective solar energy capture in the daylight hours, before ending at 7 P.M. Grid purchase, essential from 9 A.M. to 7 P.M., peaks at 169.30 kW at 4 P.M., showing a significant dependency on grid energy. The absence of grid sales throughout the month implies no surplus energy exportation. Total load achieves its highest at 217.72 kW around 1 P.M. and then gradually decreases, correlating with the trends in PV generation and grid dependency. July's data reveals an almost negligible use of battery storage, with minor increments only at specific hours. PV power output remains null during the night and starts to climb at 7 A.M. The power peaks at 155.98 kW at 1 P.M., indicating robust solar energy production in this summer month. Grid purchase becomes necessary from 9 A.M. to 7 P.M., reaching its highest point of 101.95 kW at 5 P.M. This supplements the energy demands beyond what solar output can provide. Like the previous months, grid sales are consistently non-existent. The total load shows a peak of 169.91 kW at noon, reflecting the solar output and grid purchase patterns. The battery SoC in October begins at zero, gradually increasing from 7 A.M. to a peak of 30.38% at 3 P.M. then declines, indicating battery utilization during daylight. PV power output is nil during early morning hours, starting at 7 A.M., peaks at 178.74 kW at 1 P.M., and ceases by 6 P.M., showcasing effective solar energy generation. Grid purchase is mainly required from 9 A.M. to 7 P.M., with the peak demand of 143.35 kW at 7 P.M., reflecting the reliance on grid power. Similar to other months, there is no grid sale throughout October. The total load pattern aligns with the PV output and grid purchases, peaking at 190.16 kW around noon.

4.5.6. Annualized Carbon Emission

Table 7 outlines the environmental impact of the office charging station in terms of air pollutants, quantifying the emissions associated with its operations. Annually, the station is responsible for emitting 173,956 kg of carbon dioxide (CO_2), 754 kg of sulfur dioxide (SO_2), and 369 kg of nitrogen oxide (NOx). These figures reflect the station's carbon footprint and contribution to air pollution, emphasizing the importance of sustainable practices and the potential benefits of transitioning toward cleaner and renewable energy sources.

Table 7. Environmental impact assessment.

Quantity	Value	Unit
Carbon Dioxide	173,956	kg/year
Sulfur Dioxide	754	kg/year
Nitrogen Oxides	369	kg/year

4.5.7. Optimizing Sustainability and Efficiency: A Comparative Assessment of Base and Proposed Charging Station Systems

This financial and environmental analysis compares the base system with the proposed system for an office charging station is depicted in Table 8. The proposed system demonstrates remarkable financial efficiency, evidenced by an impressive Internal Rate of Return (IRR) of 95.9%, and rapid payback periods—1.11 years for the discounted payback and an even shorter 1.04 years for the simple payback. From a cost perspective, the NPC of the proposed system (USD 1.52 million) is significantly lower than that of the base system ($2.71 million). This reduction is achieved through a strategic balance of capital expenditure (CAPEX) and operational expenditure (OPEX). While the proposed system has a higher CAPEX of USD 300,359 compared to the base system's USD 195,570, it compensates with a substantially lower OPEX of USD 94,516, compared to the base system's USD 194,126. The levelized cost of electricity (LCOE) further underscores the cost-effectiveness of the proposed system. It shows a reduction to USD 0.192 per kWh, almost half of the base system's USD 0.349 per kWh. This lower LCOE reflects the greater efficiency and cost savings over the lifespan of the proposed system. In terms of environmental impact, the proposed system significantly reduces carbon dioxide emissions, lowering it to 173,956 kg/year compared to the base system's 378,432 kg/year. This substantial decrease highlights the proposed system's role in promoting a more sustainable and environmentally friendly operation for the office charging station.

Table 8. Comparative analysis of financial metrics and environmental impact between base and proposed systems for office charging stations (amounts are given in USD ($)).

	Base System	Proposed System
Net Present Cost	$2.71 M	$1.52 M
CAPEX	$195,570	$300,359
OPEX	$194,126	$94,516
LCOE (per kWh)	$0.349	$0.192
CO_2 Emitted (kg/year)	378,432	173,956

The WPT prototype ensures seamless integration with the existing grid infrastructure, addressing key challenges in stability, power quality, and regulation. In the case study, the converter manages energy flow between the PV system, Tesla Powerwall 2.0 batteries, and the grid, establishing a reliable power source and backup. Financially efficient, with a USD 1.52 million NPC and a robust 95.9% IRR, the system minimizes grid reliance by generating 56.7% of power from solar energy. Monthly transactions optimize sustainability, reducing carbon emissions to 173,956 kg CO_2 annually, illustrating its effectiveness in enhancing grid stability and adhering to regulatory standards.

4.6. Limitations, Challenges, Significance, and Implications of Results

The results present a robust prototype for WPT integrated with RERs for sustainable EV charging. However, critical analysis reveals challenges and limitations that must be addressed for real-world implementation. The prototype's reliance on solar energy introduces uncertainties tied to inconsistent sunlight, impacting system efficiency. The charging automation system, dependent on IoT sensors, may face challenges in accurately detecting and initiating charging, especially in dynamic parking environments. Practical implications and the scalability of the model, including charging automation, require thorough exploration to ensure effectiveness across diverse settings. These considerations emphasize the need for addressing challenges and uncertainties for successful real-world deployment of WPT systems.

The financial overview highlights the proposed system's efficiency with an impressive internal IRR of 95.9% and a lower NPC of USD 1.52 million compared to the base system. Monthly energy transactions highlight strategic reliance on grid energy during peak demand, offering insights for optimizing energy management. Environmental considerations demonstrate a significant reduction in annual carbon emissions to 173,956 kg of CO_2, reflecting the system's commitment to sustainability. The comparative assessment underscores the proposed system's financial viability, environmental benefits, and potential to establish a more sustainable and efficient office charging station.

5. Conclusions

In conclusion, the research introduces a novel approach to EV charging by integrating WPT, RERs, and IoT. This innovation not only promotes sustainability by utilizing renewable energy but also enhances user convenience through automatic vehicle detection and real-time monitoring via the Blynk application. The incorporation of RFID technology ensures both efficiency and security, marking a transformative shift in EV infrastructure. In the case study, the PV and BESS integrated system in the office charging station proves to be a financially efficient and sustainable energy solution. Despite the upfront investment of USD 300,359, the system boasts an impressive IRR of 95.9% and a lower NPC of USD 1.52 million compared to the base system. The PV system contributes 56.7% of the total power output, generating 635,349 kWh annually, while the BESS demonstrates efficient energy storage with an autonomy of 5.79 h. Monthly energy transactions reveal strategic reliance on grid energy during peak demand, offering valuable insights for optimizing energy management. Environmental considerations indicate the system's commitment to sustainability, with annual carbon emissions reduced to 173,956 kg of CO_2. This substantial decrease aligns with global efforts to combat climate change and highlights the positive impact of renewable energy integration. In essence, the PV and BESS integrated system not only meets financial and efficiency criteria but also sets a model for sustainable energy practices in corporate settings, emphasizing long-term economic and environmental benefits.

Limitations and Future Work

The study mainly considered an office charging station context. Consequently, broader applicability requires further investigation. Future research should focus on scalability, energy algorithm optimization, machine learning integration, and addressing regulatory challenges for widespread adoption of sustainable EV charging solutions.

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