

A Comprehensive Review EV Charging Using Solar Energy with IOT-Based Data Monitoring

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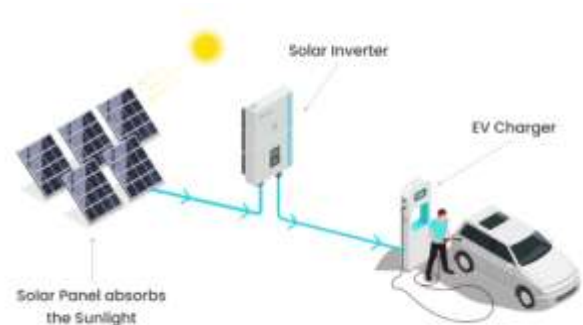
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Abstract— Electric vehicles (EVs) are rapidly gaining popularity as sustainable alternatives to conventional gas-powered vehicles that rely on batteries for operation. Although grid-based EV charging is the current standard, solar-powered EV chargers present a promising alternative by providing clean energy and contributing to environmental conservation. This project focuses on designing and developing an advanced solar-powered EV charging station integrated with Internet of Things (IoT) technology. The charging station harnesses solar energy to charge EV batteries, offering a cost-effective and eco-friendly solution. The key components include solar panels, energy storage systems, and smart grid connectivity, all of which are managed by an Arduino UNO and ESP8266 Wi-Fi module. Real-time data, such as current, voltage, and energy consumption, were monitored and uploaded to an IoT platform, allowing remote access and analysis of the charging process. Additionally, the system is connected to the grid for real-time tariff rate monitoring and optimizes charging based on cost-efficiency. For demonstration purposes, a motor was used to simulate the EV load, which showcased how the system could manage and control the power flow. This project highlights the integration of renewable energy with smart technologies to create a sustainable transportation ecosystem, addressing the critical issues of energy sustainability and carbon footprint reduction.

I. INTRODUCTION



The increasing global emphasis on reducing carbon emissions and the environmental impacts of fossil fuels has made electric vehicles (EVs) a key player in transforming transportation systems. Unlike conventional internal combustion engine vehicles, EVs rely entirely on electricity, which is often sourced from the power grid. However, as the demand for EVs grows, so does the need for a sustainable and efficient charging infrastructure. One of the most promising solutions to this challenge is the integration of renewable energy, specifically solar power, into EV charging stations. Solar-powered charging stations offer a clean and renewable energy source, reducing dependency on the grid and minimizing the carbon footprint associated with EV charging. This project aims to design and implement a solar-powered EV charging station enhanced with IoT technology for real-time data monitoring and smart energy management. By utilizing solar panels and a battery energy storage system, the charging station harnesses renewable energy to charge EVs while offering real-

time data analytics on energy consumption, battery status, and electricity costs. IoT integration enables users to remotely monitor the station's performance, access real-time electricity tariff rates, and optimize their charging process. For demonstration purposes, the project simulated EV charging using a motor load that represented the actual EV battery. This setup demonstrates how energy consumption and charging performance can be managed using a connected platform. The introduction of the IoT in EV charging infrastructure also brings significant benefits in terms of smart grid connectivity. By integrating grid tariffs and enabling two-way communication, users can monitor the energy flow and choose the most cost-effective and eco-friendly time to charge their EVs.

II. LITERATURE SURVEY

Research on electric vehicle (EV) charging infrastructure has progressed across several interconnected domains, including wireless power transfer (WPT), dynamic wireless charging (DWC), charging station planning, grid integration, optimization techniques, Internet of Things (IoT) applications, and cyber security frameworks. Although these areas have advanced significantly, most studies have investigated them independently, creating a need for an integrated and systematic review of the field [1], [2].

Early investigations into WPT primarily focused on the feasibility and electromagnetic characteristics of stationary and dynamic charging systems for EVs. Initial findings demonstrated that inductive and resonant coupling techniques can achieve contactless energy transfer with acceptable efficiency and safety under controlled alignment conditions [3], [4], [5]. Subsequent studies expanded on this work by evaluating different compensation topologies, including series, parallel-series, dual-side LCC, and hybrid configurations under varying air gaps, impedance conditions, and coil misalignments [6]. These analyses highlighted important trade-offs among voltage stability, power transfer efficiency and tolerance to lateral or longitudinal misalignment [7].

Recent advancements have focused on adaptive coil designs and improved compensation strategies to reduce the alignment sensitivity and efficiency degradation. For instance, the Adaptive Coil and

Compensation Integration Framework (ACCIF) demonstrated efficiencies exceeding 94%, even with larger air gaps, indicating improved scalability and robustness for EV charging applications [8]. Similarly, auxiliary LCR coil-based positioning mechanisms achieved an alignment accuracy within 10 mm, addressing one of the key operational limitations of WPT systems. Despite these technical improvements, increased system complexity and implementation costs remain major concerns that are often overlooked in previous surveys [9], [10].

Control strategies, such as Maximum Efficiency and Power Tracking (MEPT), have further enhanced system reliability during load fluctuations and dynamic interruptions by improving both efficiency and operational stability compared with conventional methods. However, comparing results across studies remains difficult because researchers frequently use different evaluation metrics, operating frequencies, and experimental assumptions [10], [11].

Dynamic wireless charging has attracted growing attention because of its potential to extend the EV driving range and reduce battery size requirements. Several studies have explored DWC deployment on highways, urban roads, and motorways, revealing that the charging performance strongly depends on the road type, vehicle speed, and charging lane length [12], [13], [14]. Urban environments generally benefit from lower vehicle speeds and stronger coupling consistency, whereas highway applications face challenges related to intermittent coupling and high infrastructure costs.

Researchers have proposed traffic-aware and behavior-based control strategies to improve DWC performance. Approaches such as platoon coordination and adaptive lane management have shown improvements in both traffic flow and charging efficiency when supported by connected vehicle technologies [15], [16]. Nevertheless, these investigations are often simulation-based, relying heavily on platforms such as SUMO and assuming high penetration rates of connected vehicles, which may limit their short-term practical implementation.

Large-scale system studies have examined the influence of DWC on regional power networks. Analyses using the ERCOT transmission model and Canadian highway systems suggested that in-motion

charging could reduce operational costs and better align EV energy demand with renewable energy generation, particularly in scenarios with high renewable penetration. However, inconsistent assumptions regarding EV adoption rates, charging profiles, and infrastructure density highlight the lack of standardized evaluation methodologies [17].

Another major research focus is the planning and optimal placement of EV charging stations and DWC infrastructure. Multi-objective and bi-level optimization models have been widely adopted to balance system-wide objectives and user behavior. Techniques that integrate stochastic user equilibrium, surrogate optimization, and budget-constrained planning have been demonstrated to be effective in minimizing social costs while maintaining profitability [18], [19].

Microgrid-based charging systems have also been investigated for use in EVs as distributed energy storage resources. Bi-level optimization approaches confirmed the feasibility of coordinating renewable energy generation, charging demand, and grid operation under various conditions. Probabilistic demand models based on Monte Carlo simulations and real-world travel datasets further emphasize the importance of smart charging strategies for maintaining grid stability [20]. In distribution networks, fast inductive charging systems introduce voltage and thermal constraints that may hinder large-scale deployment unless the grid infrastructure is upgraded. Research on shared charging infrastructure for EVs and unmanned aerial vehicles (UAVs) has also demonstrated cost and efficiency advantages, although such systems introduce additional coordination challenges [21], [22].

Modern smart charging strategies increasingly incorporate predictive analytics, clustering methods, and game-theoretic approaches. Iterative clustering of EV charging time-series data proved effective for identifying charging behavior patterns despite noisy datasets, thereby supporting demand forecasting and grid-planning. Similarly, pricing and routing models based on Stackelberg game theory reduce peak demand while balancing the interests of charging operators and EV users.

In addition to technical considerations, several studies have examined user acceptance and the behavioral

factors affecting DWC adoption. Survey-based analyses conducted in locations such as New Zealand and Seoul revealed that perceived usefulness, environmental awareness, and charging convenience strongly influence public acceptance, whereas safety concerns continue to represent a major barrier. These findings suggest that technological advancement alone is insufficient without corresponding policy support and public confidence.

IoT-enabled communication technologies are essential components of intelligent EV charging systems. Research on standards such as ISO 15118 and Plug-and-Charge authentication has identified vulnerabilities in communication protocols and emphasized the need for secure authentication and key management mechanisms. OCPP-based charging management systems have improved load balancing, dynamic pricing, and network security in large-scale charging infrastructure. Advanced cybersecurity techniques, including federated learning and privacy-preserving intrusion detection systems, have demonstrated high detection accuracy without requiring centralized data exchange, making them suitable for distributed electric vehicle (EV) charging environments. However, most cybersecurity studies focus primarily on communication layers, with limited investigations into the interactions between communication protocols, WPT hardware, and real-time control mechanisms.

Several studies have explored the integration of renewable energy resources with EV charging infrastructure. Solar photovoltaic (PV)-powered roadside wireless charging systems have demonstrated both environmental and economic benefits by reducing dependence on conventional grids and lowering carbon emissions. Residential microgrid-based charging systems similarly reduce peak electricity demand and operational costs through optimized energy management strategies. Integrated planning approaches that simultaneously consider renewable deployment and EV charging infrastructure have provided valuable insights into long-term sustainable energy planning [11]

Emerging technologies in this area include robotic charging systems, vision-assisted alignment mechanisms, and multisector infrastructure planning models [3], [4], [5]. Automated charging systems utilizing robot operating systems (ROS), real-time computer vision, and depth-sensing technologies have

significantly improved charging precision and user convenience. Additionally, small-world network-based planning frameworks enhance infrastructure resilience and connectivity under uncertain demand growth conditions. Multi-criteria decision-making approaches further emphasize the importance of coordinated technical, regulatory, and policy measures to accelerate global EV charging infrastructure development [6], [7].

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Microgrid-based charging systems have also been investigated for use in EVs as distributed energy storage resources. Bi-level optimization approaches confirmed the feasibility of coordinating renewable energy generation, charging demand, and grid operation under various conditions. Probabilistic demand models based on Monte Carlo simulations and real-world travel datasets further emphasize the importance of smart charging strategies for maintaining grid stability [2]. In distribution networks, fast inductive charging systems introduce voltage and thermal constraints that may hinder large-scale deployment unless the grid infrastructure is upgraded. Research on shared charging infrastructure for EVs and unmanned aerial vehicles (UAVs) has also demonstrated cost and efficiency advantages, although such systems introduce additional coordination challenges [1], [2].

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III. TAXONOMY

This section presents the taxonomy of this review for the study of EV charging using solar energy with IoT-based data monitoring Various research papers Fig. 2.



Fig. 2. Taxonomy of EV Charging Using Solar Energy with IoT-Based Data Monitoring

IV. COMPARATIVE ANALYSIS

This section presents a comparative analysis of the existing methodologies used for grid-stability-based EV charging systems. The methodologies, advantages, limitations, and performance criteria were considered for comparison. The Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Square Error (MSE), accuracy, precision, peak demand, cost demand, voltage deviation, energy losses, f1-score, Integral Absolute Error (IAE) and daily active losses are some of the parameters

V. CHALLENGES

Although solar-powered EV charging with IoT monitoring is a sustainable and intelligent solution, several technical, operational, and economic challenges limit its large-scale implementation.

- Solar energy is not constant and depends on environmental conditions, such as sunlight intensity, weather changes, time of day, and seasonal variations. This causes fluctuations in power generation, making it difficult to maintain a stable energy supply for EV charging without backup systems in place.
- The system requires multiple components, such as solar PV panels, MPPT controllers, battery storage units, power converters, and IoT devices. The integration of both energy and communication systems increases the installation cost and makes the overall system more complex to design and maintain.
- Battery energy storage systems are necessary to store excess solar energy; however, they have

limitations, such as limited capacity, degradation over time, long charging times, and high replacement costs. These constraints affect the continuous availability of the stored energy.

IoT-based monitoring relies on communication networks such as Wi-Fi, GSM, and Bluetooth. In many cases, network coverage may be weak or unstable, leading to issues such as data transmission delays, signal loss, and unreliable remote monitoring

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