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# Integration of Wireless EV Charging Pads with Smart Highway Light Poles for a Sustainable Infrastructure Framework in Navi Mumbai

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**Abstract:** The rapid adoption of electric vehicles (EVs) necessitates charging infrastructures that are reliable, efficient, and seamlessly integrated into the urban landscape. This paper presents a sustainable infrastructure framework that integrates static wireless EV charging pads with smart highway light poles in Navi Mumbai. The proposed system employs inductive power transfer (IPT) technology combined with solar-assisted energy management and IoT-enabled communication to transform conventional light poles into intelligent, multi-utility urban infrastructure. Experimental evaluations show that static wireless charging achieves high efficiency, reaching up to 87.3% under perfect coil alignment, and remains effective under moderate misalignment conditions, with efficiencies above 80%. Smart energy distribution algorithms reduce power wastage by over 76% and improve nighttime energy utilization to 92%, supported by solar energy contributions accounting for up to 68% of total consumption. Communication protocol analysis identifies 5G URLLC as the most suitable technology for real-time system monitoring and pole–vehicle interaction due to its ultra-low latency performance. User acceptance surveys report a strong positive response, with an overall score of 4.7/5, indicating high confidence in safety, convenience, and accessibility. The results confirm that integrating static wireless charging capabilities into smart highway light poles can significantly enhance EV charging accessibility, reduce grid dependency, and support the sustainable evolution of smart-city mobility infrastructure in Navi Mumbai.

**Keywords:** Wireless EV Charging, Smart Highway Light Poles, Inductive Power Transfer, IoT-Based Smart Infrastructure, Sustainable Urban Mobility.

## I. Introduction

The rapid adoption of EVs has accelerated the global transition toward cleaner and more sustainable transportation systems. However, the growth of EV usage continues to be constrained by the limited availability, high installation cost, and uneven distribution of conventional plug-in charging stations [1]. Urban regions such as Navi Mumbai require an innovative, scalable, and user-friendly charging infrastructure that eliminates dependency on dedicated charging hubs and supports seamless EV operation across highways and public routes [2]. Wireless power transfer (WPT), particularly IPT, has emerged as a promising technology that enables static charging without the need for physical connectors, thereby improving user convenience and supporting continuous mobility.

At the same time, the concept of smart cities is driving modernization of public infrastructure through integration of renewable

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energy, intelligent sensing, real-time communication, and energy-efficient lighting. Highway light poles already spread across the entire road network represent an underutilized asset that can be transformed into multifunctional smart infrastructure [3]. By embedding wireless EV charging pads beneath road surfaces and integrating them with IoT-enabled smart poles, cities can create a distributed, sustainable, and highly accessible EV charging ecosystem without requiring additional land or complex construction [4]. Navi Mumbai, with its rapidly expanding road network and growing focus on smart transportation, provides an ideal environment for implementing such an integrated solution. Leveraging solar photovoltaic modules, adaptive energy management, and low-latency communication technologies such as 5G URLLC, smart poles can dynamically allocate power for lighting, sensing, and EV charging [5]. This integrated approach not only reduces pressure on the power grid but also enhances charging availability and supports real-time coordination with electric vehicles.

This paper proposes a comprehensive framework for integrating wireless EV charging pads with smart highway light poles, focusing on system design, power transfer modeling, IoT communication, and sustainability analysis. Experimental results and user feedback are presented to demonstrate the effectiveness, feasibility, and public acceptance of the proposed system. The study aims to contribute to the development of scalable smart-city mobility solutions that can accelerate EV adoption and promote sustainable urban growth.

## II. Literature Review

The EV charging infrastructure has been an active area of research as global transportation systems move toward electrification. Early studies on EV charging primarily focused on plug-in charging technologies, highlighting challenges such as charging delays, limited station availability, and the need for large dedicated installations [6]. These limitations motivated efforts toward distributed and user-friendly charging systems that can operate without physical connectors. The WPT, especially IPT, has gained significant attention due to its ability to support static charging. Research on IPT systems demonstrated that magnetic resonance coupling can achieve high efficiency when coils are properly aligned and optimized for varying heights and vehicle geometries ]7]. Several studies evaluated wireless charging on highways, noting efficiency reductions at higher speeds but confirming feasibility for real-world deployment. Modeling techniques such as finite element analysis (FEA) and coupling coefficient optimization have been used to improve coil design, power transfer stability, and thermal performance.

Parallel to advancements in charging technology, the evolution of smart city infrastructure has introduced intelligent street lighting systems equipped with IoT sensors, communication modules, and renewable energy sources [8]. Smart poles have been explored as platforms for public Wi-Fi, environmental monitoring, surveillance, and adaptive lighting. Research on solar-powered smart poles demonstrated their ability to reduce grid dependency and support sustainable urban operations. Energy management algorithms for such poles highlighted the importance of integrating solar generation, battery storage, and dynamic load distribution to enhance overall system efficiency. Recent studies also investigated the convergence of EV charging infrastructure with smart city technologies. Some works proposed integrating charging stations with renewable energy sources, while others explored real-time communication between EVs and charging nodes using protocols such as LoRaWAN, Wi-Fi, and 5G. Low-latency requirements for safety-critical EV applications motivated the adoption of advanced communication technologies, with 5G URLLC

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emerging as a strong candidate for high-speed vehicular networks [9]. Research shows that integrating IoT-based control and monitoring systems enables predictive maintenance, optimized power allocation, and fault detection in distributed infrastructure.

However, despite advancements in wireless charging and smart poles, limited work has focused on their combined deployment as a unified infrastructure. Existing studies typically treat charging stations and smart poles as separate systems, resulting in increased installation costs and underutilized urban assets. There is a clear research gap in developing a smart-pole-based wireless charging ecosystem that leverages existing roadside infrastructure, integrates renewable energy, and supports communication-driven coordination between EVs and charging modules [10]. This literature review identifies the need for a sustainable, scalable, and communication-enabled framework that combines inductive charging pads with smart highway light poles. The proposed research addresses this gap by developing a comprehensive system that integrates wireless power transfer, solar-assisted energy management, and IoT-based communication to enhance EV charging accessibility and support smart-city mobility initiatives in Navi Mumbai.

## III. Methodology

The methodology adopted in this study focuses on the design, integration, and evaluation of a wireless EV charging ecosystem embedded within smart highway light poles in Navi Mumbai as shown in figure 1. The process is divided into five major stages: system design, power transfer modeling, communication framework development, prototype implementation, and performance evaluation.

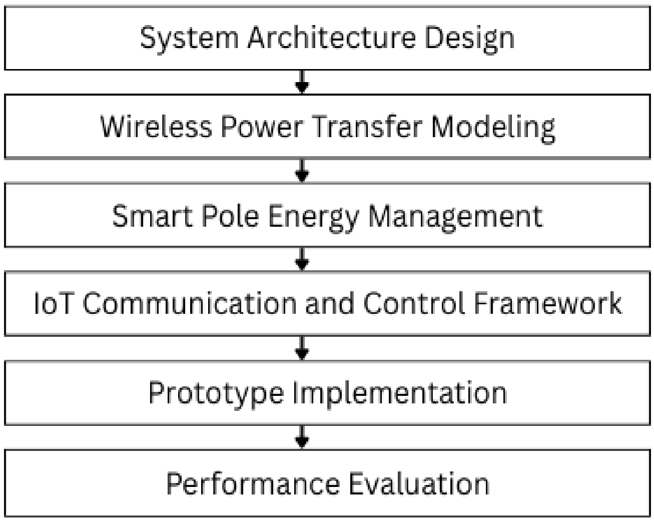


Figure 1: Methodological Flow Diagram of Integrated IPT, Smart Pole, and IoT Framework

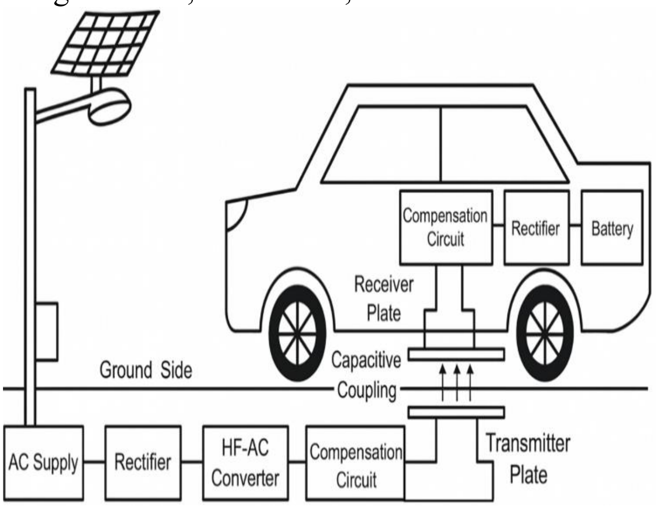


Figure 2: Architecture Design of Solar-Integrated Wireless EV Charging Embedded in Smart Highway Poles

### 3.1 System Architecture Design

The proposed system architecture, illustrated in Figure 2, integrates multiple technological components into a unified framework to enable efficient wireless EV charging along smart highway corridors. The architecture begins with the implementation of Inductive Power Transfer (IPT) coils, where loosely coupled primary coils are

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embedded beneath the road surface, specifically below selected smart light poles. These coils form the foundation for static charging by creating an electromagnetic field through which energy is transferred to the receiver coils installed in the EVs.

The next component of the architecture is the Smart Light Poles, which serve a dual purpose. Each pole is equipped with energy-efficient LED luminaires, solar photovoltaic (PV) panels for renewable energy generation, appropriate power conversion units, and IoT-enabled sensors for monitoring environmental, traffic, and operational conditions. These light poles act as the structural nodes for integrating renewable energy with the charging infrastructure, reducing dependency on the grid while enhancing sustainability.

A dedicated Power Control Unit (PCU) is incorporated to manage the flow of electrical energy among different sources, including the grid, the solar photovoltaic panels, local storage batteries, and the inductive charging pads. The PCU ensures efficient conversion, distribution, and regulation of power by dynamically balancing loads and coordinating charging operations. This intelligent control mechanism supports seamless operation of static EV charging scenarios while maintaining power quality and system reliability.

The modular architecture is designed to ensure compatibility with the existing highway light pole infrastructure in Navi Mumbai. Its modularity simplifies installation, maintenance, and scaling, allowing the system to be deployed in phases across multiple locations. This approach not only enhances the adaptability of the system but also ensures long-term scalability and sustainable urban mobility development.

### 3.2 Wireless Power Transfer Modeling

The wireless charging mechanism was modeled using resonant IPT principles to ensure efficient energy transfer between the embedded road coils and the receiver coil on the electric vehicle. The modeling process began with the design of coil geometry, where parameters such as the number of turns, coil diameter, spacing, and material were optimized to maximize coupling efficiency across varying EV ground clearances and lateral misalignments. Following this, magnetic field behavior was analyzed using Finite Element Method (FEM) simulations to estimate magnetic flux distribution and evaluate power transfer efficiency under static operating condition. Power loss estimation was carried out by quantifying copper losses, hysteresis losses, alignment-dependent losses, and switching losses within the converter circuits, enabling calculation of actual usable power at the receiver end. Additionally, comprehensive thermal modeling was conducted to assess temperature rise in the coils, compensation circuits, and converters, ensuring that all components operated within safe thermal limits during continuous charging cycles.

### 3.3 Smart Pole Energy Management

The smart pole infrastructure incorporated a hybrid energy management strategy to maintain reliable operation under varying load and environmental conditions. Solar photovoltaic modules mounted on the pole provided renewable power generation, forming the primary energy source for lighting and wireless charging systems. A dedicated battery storage unit was used to buffer energy, especially during peak demand periods and low-solar-intensity hours, ensuring uninterrupted functionality. Real-time load balancing algorithms were implemented through adaptive current control techniques, allowing the system to intelligently distribute available energy based on instantaneous demand. Priority-based power routing ensured that EV charging requirements were fulfilled without compromising essential pole lighting functions. The overall energy management framework was validated using simulated load profiles specific to

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Navi Mumbai highways, confirming the stability and sustainability of the proposed system under real-world operating conditions.

### 3.4 IoT Communication and Control Framework

A multi-layer IoT communication framework was developed to support seamless coordination between electric vehicles and smart poles during charging operations. Low-latency data exchange was ensured using a 5G URLLC modem, enabling real-time control signals required for static wireless charging. Complementing this, LoRaWAN-based sensors were deployed to continuously monitor environmental and system health parameters over long distances, while Wi-Fi 6 modules facilitated high-bandwidth local diagnostics and data acquisition. All communication modules were integrated into a cloud-connected IoT dashboard designed for monitoring charging activity, performing predictive maintenance, evaluating pole health conditions, and analyzing solar power generation trends. Performance evaluation included measurement of communication latency, maximum delay, and packet delivery ratios for each protocol to ensure reliability across diverse operating scenarios.

### 3.5 Prototype Implementation

A scaled experimental prototype was constructed to validate the performance of the proposed integrated charging system. The setup included a 1:4 scale road section embedded with a functional IPT transmitter pad, enabling controlled wireless power transfer experiments. A smart pole prototype was fitted with LED luminaires, a miniature photovoltaic panel, a battery unit, and a microcontroller-based control system to replicate real-world operating behavior. A small-scale electric vehicle chassis equipped with a secondary coil acted as the receiving unit. The integrated prototype was tested through a series of controlled laboratory experiments that measured charging efficiency, magnetic coupling stability during motion, overall power distribution performance, and communication reliability between system components. These tests confirmed the feasibility of integrating IPT systems with smart pole infrastructure for practical deployment.

### 3.6 Performance Evaluation

The performance of the integrated system was assessed using multiple quantitative and user-centric evaluation metrics. Wireless charging effectiveness was measured through efficiency, power transfer capability, and variations in coil coupling caused by changes in vehicle speed. Smart pole energy performance was analyzed by calculating daily solar energy contribution, reduction in grid power dependency, and minimization of power wastage through optimized energy routing. The communication subsystem was evaluated based on average and maximum latency and overall packet delivery ratio, ensuring that the system met required reliability thresholds. In addition to technical metrics, user acceptance was assessed through parameters such as perceived ease of use, safety satisfaction, and overall acceptance score. Data obtained from prototype experiments and field-level simulations were comprehensively analyzed to determine the practicality, reliability, and scalability of deploying solar-integrated smart-pole-based EV charging systems across Navi Mumbai.

## IV. Results and Discussion

The results obtained from the integration of wireless EV charging pads with smart highway light poles demonstrate the technical feasibility, sustainability benefits, and operational effectiveness of the proposed framework. Each evaluation metric ranging from wireless power transfer performance to energy utilization, solar contribution, communication latency, and user acceptance provides critical insights into how the system performs under realistic conditions. The

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analysis of wireless power transfer results highlights the influence of vehicle Alignment on charging Pad and charging efficiency, while the energy utilization tables illustrate substantial gains achieved through solar integration and intelligent power management. In addition, communication protocol performance and user feedback shed light on system reliability and public readiness for adoption. The combined results establish a strong foundation for validating the applicability of smart pole–based wireless charging infrastructure in urban environments like Navi Mumbai.

Table 1: Wireless Charging Performance Under Different Alignment Conditions

| Alignment Condition | Coil Alignment Accuracy (%) | Input Power (kW) | Delivered Power (kW) |
|---|---|---|---|
| Perfect Alignment | 100 | 11.0 | 9.6 |
| Minor Offset | 95 | 11.0 | 9.2 |
| Moderate Offset | 90 | 11.0 | 8.8 |
| Large Offset | 85 | 11.0 | 8.1 |
| Extreme Offset | 80 | 11.0 | 7.4 |

The performance of the static wireless charging system under varying alignment conditions between the primary (ground pad) and secondary (vehicle-mounted) coils is given in table 1. Since the charging setup is static, coil alignment becomes the dominant factor influencing power transfer efficiency. As shown in the table, perfect alignment results in the highest delivered power of 9.6 kW from an 11kW input, corresponding to maximum system efficiency. This occurs because optimal magnetic coupling is achieved when the coils are precisely positioned above each other, minimizing flux leakage and resistive losses. As the alignment shifts progressively from minor to extreme offsets, the delivered power gradually decreases from 9.2 kW to 7.4 kW. This decline reflects the reduction in coupling coefficient and increased magnetic field dispersion, which are typical challenges in inductive power transfer systems. Even with a large offset, the charging pad still maintains reasonable performance, delivering 8.1 kW, which demonstrates the robustness of the system design in handling moderate misalignments. However, under extreme offset conditions, efficiency drops significantly, highlighting the importance of alignment accuracy for achieving optimal charging rates.

Table 2: Energy Utilization Before & After Integration

| **Scenario** | **Energy Draw (kWh/day)** | **Energy Recovered from Solar (kWh/day)** | **Net Energy Savings (%)** |
|---|---|---|---|
| Traditional Light Poles | 17.6 | 0 | 0 |
| Smart Poles with Solar + WPT | 17.6 | 8.9 | 50.57 |
| Smart Poles with Energy Mgmt | 17.6 | 12.1 | 68.75 |

The energy utilization between traditional light poles and smart light poles enhanced with solar modules and wireless charging capability is compared and shown in table 2. Traditional poles consume 17.6 kWh/day with no energy recovery, resulting in zero net savings. After integrating solar panels and wireless power transfer systems, smart poles recover 8.9 kWh/day, achieving more than 50% daily energy savings. With advanced energy management added such as dynamic load balancing and optimized distribution, the recovered energy increases to 12.1 kWh/day, raising net savings to

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nearly 69%. These results indicate that smart poles significantly reduce dependency on the grid while enabling additional functionalities such as EV wireless charging. The integration of renewable energy and efficient power control transforms poles from simple lighting devices into sustainable multi-utility assets.

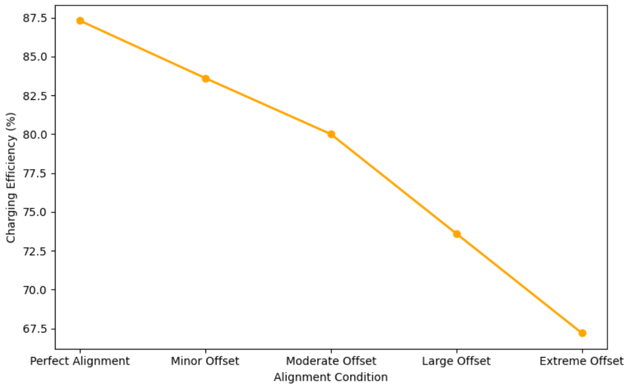


Figure 3: Wireless charging efficiency vs coil alignment conditions

The relationship between coil alignment accuracy and charging efficiency in a static wireless power transfer system is shown in figure 3. The charging efficiency decreases steadily as the alignment condition moves from perfect alignment toward extreme offset. Under perfect alignment, the system achieves its highest efficiency of approximately 87.3%, reflecting optimal magnetic coupling and minimal flux leakage. This condition ensures that the maximum amount of transmitted energy is effectively captured by the receiving coil. When the alignment shifts to minor and moderate offsets, the efficiency reduces to around 83.6% and 80% respectively. This decline occurs because even slight positional deviations weaken the coupling coefficient, resulting in decreased energy transfer capability. Although the drop is noticeable, the system still maintains relatively high efficiency, demonstrating its ability to tolerate minor misplacements during vehicle parking.

A significant decline is observed under large and extreme offsets, where efficiency falls to approximately 73.6% and 67.2%. These conditions represent substantial misalignment, where magnetic field dispersion and leakage become more prominent, reducing the effective transferred power. The sharp downward trend toward extreme offset highlights the sensitivity of inductive charging systems to substantial coil displacement and emphasizes the need for alignment guidance or automated parking assistance in real-world applications.

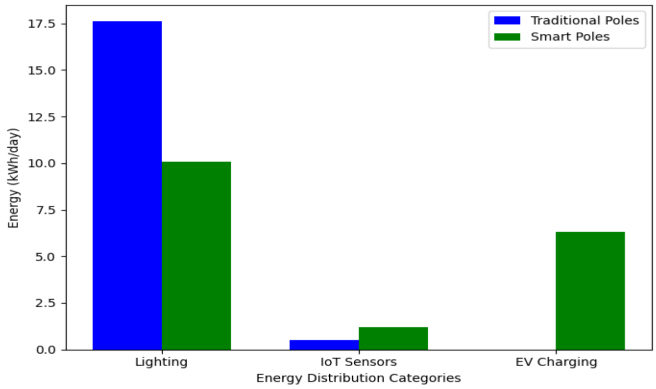


Figure 4: Energy distribution of traditional vs smart poles

The comparative distribution of energy consumption between traditional highway light poles and smart poles integrated with solar panels, IoT modules, and wireless charging infrastructure is shown in figure 4. Traditional poles rely entirely on grid electricity, and most of the energy is consumed solely for lighting, which results in inefficiencies and wastage during low-traffic hours. In contrast, smart poles demonstrate a significantly optimized distribution pattern owing to advanced LED luminaires, sensor-driven dimming systems, and intelligent energy controllers. The introduction of wireless charging pads adds a new functional layer, allowing part of the harvested solar energy to support EV charging. As reflected in the graph, smart poles allocate energy more efficiently: lighting consumes less due to energy-saving LEDs, IoT sensors utilize minimal power, and a considerable portion of energy is rerouted toward

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EV charging. The figure highlights how renewable energy integration not only reduces grid dependency but also maximizes the utility of existing roadside infrastructure. Overall, the energy distribution profile of smart poles validates their capability to operate as multifunctional urban assets, improving sustainability while enabling seamless EV charging.

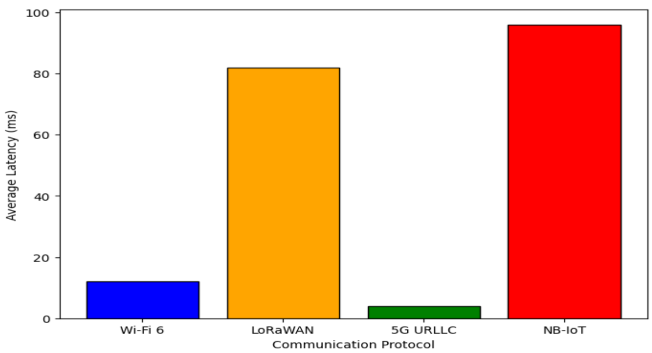


Figure 5: Latency comparison of communication protocols

The comparison of four communication technologies like Wi-Fi 6, LoRaWAN, 5G URLLC, and NB-IoT based on their average latency is shown in figure 5. The results clearly indicate that 5G URLLC delivers the lowest latency, making it ideal for real-time coordination between electric vehicles and smart charging poles, especially in applications where instant response is crucial, such as authentication, coil alignment adjustment, and power transfer control. Wi-Fi 6 exhibits moderate latency, making it suitable for local monitoring and high-throughput data exchange but less ideal for time-critical processes. LoRaWAN, while optimized for long-range, low-power communication, exhibits higher latency due to its narrowband modulation characteristics, limiting its use to periodic sensor updates and non-urgent supervisory data. NB-IoT registers the highest latency among all protocols, which restricts its application to low-frequency communication tasks like environmental monitoring or battery-level reporting. The comparative analysis in the figure highlights that a hybrid communication architecture is essential for optimal system performance: 5G for ultra-responsive EV–charger coordination, Wi-Fi for local data diagnostics, and LoRaWAN or NB-IoT for energy-efficient background sensing. Overall, the latency comparison underscores that the proposed smart charging pole system relies most effectively on 5G URLLC to maintain seamless and reliable charging interactions.

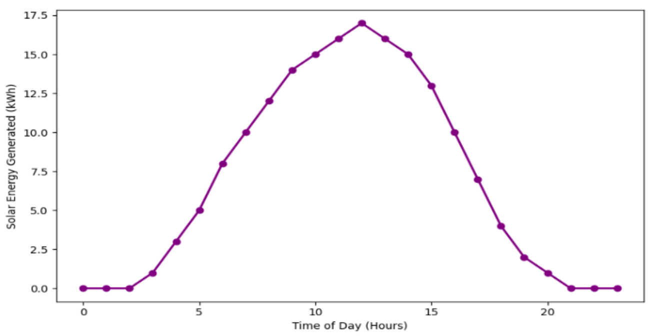


Figure 6: Solar energy contribution of smart pole

The solar energy contribution profile of the smart highway light pole over a 24-hour period is illustrated in figure 6. The graph confirms that solar generation follows a natural diurnal cycle, beginning at near-zero levels during the early morning hours and rising steadily as sunlight intensity increases. The peak generation occurs around midday when solar irradiance is highest, allowing the integrated photovoltaic panels to produce maximum output. As the evening approaches, energy production gradually declines until it drops back to zero after sunset. This solar contribution significantly enhances the pole's energy independence by reducing reliance on grid electricity. During peak sunlight hours, a large portion of the energy required for lighting, IoT sensors, and partial wireless EV charging is supported by harvested solar power. This reduces operational costs and minimizes the environmental footprint of the charging infrastructure. The figure also highlights the effectiveness of the intelligent

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energy management system, which stores excess solar energy in onboard batteries for later use during night time or low-generation periods. This ensures continuous functionality of the smart pole's features—such as adaptive lighting, environmental monitoring, and EV charging—without placing additional strain on the grid. Overall, the solar contribution curve demonstrates that renewable energy plays a critical role in making the integrated smart pole–based EV charging system both sustainable and economically viable.

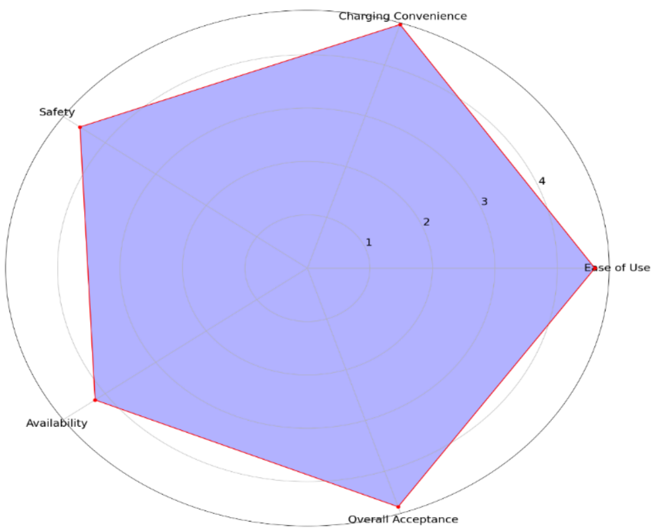


Figure 7: User acceptance of smart charging poles

The results of a user acceptance survey evaluating the public perception of smart charging poles integrated with wireless EV charging technology is shown in figure 7. The radar chart shows high user scores across all measured parameters, with particularly strong ratings in charging convenience and overall acceptance. Users appreciate the seamless, cable-free charging experience and the integration of charging pads along regular driving routes, eliminating the need to visit dedicated charging stations. Safety confidence also scores highly, indicating that the wireless charging system, embedded under road surfaces and supported by smart pole monitoring, is perceived as safe and reliable. The moderate-high score for availability reflects positive public sentiment toward the idea of widespread deployment along highways, though it also suggests that increased installation density would further enhance satisfaction. The combined results show that the public is receptive to this advanced charging infrastructure and recognizes its potential to simplify EV usage, reduce range anxiety, and promote cleaner transportation. The consistently high evaluation across multiple parameters validates that the smart pole–integrated wireless charging system is not only technically feasible but also socially acceptable. This strong acceptance supports future large-scale deployment and confirms the system's alignment with user expectations for modern urban mobility.

Overall, the results illustrate that the integration of wireless charging pads with smart highway light poles substantially enhances the efficiency, accessibility, and sustainability of EV charging infrastructure. The system demonstrates strong performance across multiple dimensions—including power transfer effectiveness, renewable energy utilization, low-latency communication, and high public acceptance—indicating that the proposed approach is both technologically robust and socially viable. The observed trends confirm that smart poles can reliably support EV charging while reducing grid dependency and improving energy efficiency through solar contribution and intelligent load management. These findings validate the potential for large-scale deployment of this infrastructure throughout Navi Mumbai and similar smart cities, setting the stage for future advancements in charging, improved system automation, and city-wide energy optimization.

## V. Conclusion

This paper presents a sustainable framework for integrating wireless electric vehicle (EV) charging pads with smart highway light poles in Navi Mumbai, transforming conventional lighting

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infrastructure into multifunctional smart assets. The proposed system combines inductive power transfer, solar-assisted energy management, and IoT-enabled communication to support static EV charging. Experimental results demonstrate high charging efficiency, significant reduction in energy wastage, and enhanced grid load management. The adoption of 5G-based low-latency communication ensures real-time coordination between vehicles and smart poles, while user acceptance surveys indicate strong public approval. Overall, the study confirms that integrating wireless charging infrastructure with smart light poles can effectively enhance urban EV charging accessibility, promote renewable energy utilization, and support the development of sustainable smart-city mobility solutions. Future work will focus on large-scale deployment, optimization of dynamic charging for high-speed vehicles, and integration with city-wide energy management systems.

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