

A thorough analysis of Electric Vehicle (EV) charging technologies and their effects on the Electrical Grid

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ABSTRACT

For contemporary power grids, the quick uptake of electric vehicles (EVs) offers both opportunities and difficulties, especially with regard to stability, efficiency, and the integration of renewable energy. This research uses a simulation-based method in MATLAB Simulink to study modern EV charging technologies and how they interact with the power system. To achieve optimal energy extraction, the system integrates renewable energy sources, specifically solar photovoltaics and wind turbines, with a Maximum Power Point Tracking (MPPT) boost converter. To control quick transients, extend battery life, and preserve steady DC bus voltage, a hybrid energy storage system that combines batteries and supercapacitors is used.

Bidirectional AC power flow made possible by a three-phase inverter allows for load integration, grid assistance, and effective energy sharing between EV loads, storage units, and renewable energy sources. A wide

range of measures, including as harmonic mitigation, voltage sag and swell analysis, total harmonic distortion (THD), power flow management, demand response, and overall system efficiency, are used to assess the system's performance. PI and PID controllers are examples of adaptive control systems that are used to prioritize key loads and optimize energy distribution. The outcomes of the simulation show how hybrid storage and sophisticated control methods can improve grid stability, maximize the use of renewable energy sources, and meet changing EV charging needs. The study offers insightful information on how to minimize negative effects on the electrical system while creating a reliable and sustainable EV charging infrastructure.

Index terms: Total Harmonic Distortion (THD), bidirectional AC power flow, electric vehicles (EVs), Maximum Power Point Tracking, PI, and PID controllers.

1. INTRODUCTION:

Modern power systems are changing as a result of the extensive use of electric vehicles (EVs), which present both new operational difficulties and substantial financial and environmental advantages. Voltage fluctuations, higher peak loads, and possible grid instability might result from EV charging demands, which are fundamentally unpredictable and frequently high[1]. While hybrid energy storage systems, which combine batteries and supercapacitors, can offer quick response support to balance fluctuations and maintain DC bus voltage stability, Maximum Power Point Tracking (MPPT) techniques can be used in conjunction with boost converters to maximize energy extraction[2].

Hybrid storage solutions are essential for improving EV charging infrastructures' overall performance. Supercapacitors can supply and absorb quick transient currents, which lessens the strain on batteries and increases their longevity, while batteries offer long-term energy storage[3]. These systems provide efficient power sharing between EV loads, renewable energy sources, and the grid when combined with bidirectional three-phase inverters. In addition to supporting load control, this strategy makes grid functions like voltage regulation, reactive power compensation,

and demand response easier[4]. For real-time energy flow optimization, harmonic mitigation, and important load prioritization, sophisticated control techniques such as proportional-integral (PI) and proportional-integral-derivative (PID) controllers are crucial. Researchers may model intricate interactions between EV chargers, renewable production, storage systems, and the grid under dynamic operating conditions through simulation-based investigations, especially when utilizing MATLAB Simulink. This research offers a thorough foundation for creating reliable[5], sustainable, and grid-friendly EV charging infrastructures by examining performance measures like voltage sag and swell, total harmonic distortion (THD), power flow control, and overall system efficiency.

2.PROJECT OBJECTIVE :

This project's main goal is to find ways to improve grid stability, efficiency, and dependability by integrating electric vehicle (EV) charging systems with renewable energy sources and hybrid energy storage. In order to assess the effectiveness of cutting-edge EV charging solutions under dynamic load and renewable generation situations, the study focuses on creating a simulation-based framework in MATLAB Simulink[6]. Implementing and testing adaptive control

techniques, such as PI and PID controllers, to manage rapid transients, optimize energy distribution, and guarantee effective power sharing between EV loads, renewable generation, and storage systems is a secondary goal[7]. The study intends to minimize negative effects on the electrical system while offering insights for building reliable and sustainable EV charging facilities.

3. EXISTING SYSTEM:

The conventional EV charging system uses typical unidirectional chargers and grid-supplied AC electricity. In this setup, EVs take power straight from the grid, frequently without taking energy storage integration or renewable energy sources into account[8]. The technology lacks the intelligence to adjust to grid conditions or optimize energy use, and charging happens at a set rate[9]. Furthermore, the inability of these traditional systems to facilitate bidirectional power flow restricts their capacity to offer grid services like voltage management, peak shaving, and demand response. The utilization of independent renewable-powered chargers, including PV-based charging stations, is another popular strategy in current systems. Although these systems use sustainable energy, they usually don't include hybrid storage or sophisticated energy management[10]. This leads to poor

handling of transient loads and underutilization of available renewable energy, which causes charging power fluctuations and decreased reliability.

3.1. DISADVANTAGES:

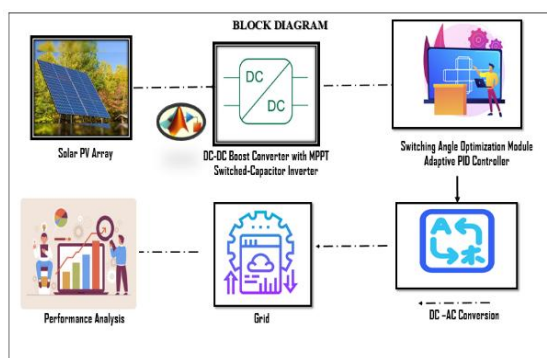
Because of uniform curtailment, overvoltage mitigation is frequently ineffective.

- Some prosumers suffer excessive energy losses; fairness among them is not taken into account.
- Does not maximize overall network efficiency or power loss[11];
- Slow and unable to react to sudden voltage swings;
- Limited adaptability to dynamic changes in load or PV generation.

4. PROPOSED SYSTEM:

The suggested technology combines a hybrid energy storage system that combines batteries and supercapacitors with renewable energy sources like solar PV and wind turbines. While a three-phase bidirectional inverter enables effective AC power supply to both loads and the grid, a DC–DC boost converter with MPPT guarantees maximal power extraction from renewables. Even in dynamic EV charging scenarios[12], adaptive control techniques like PI and PID controllers prioritize key loads, control energy flow, and preserve grid stability. Additionally, by managing

quick transient loads, the hybrid storage system extends battery life, and the bidirectional energy flow makes vehicle-to-grid (V2G) applications possible. The system is appropriate for integrating EV charging infrastructure with contemporary smart grids since it provides demand response, peak shaving, and energy balancing[13].



4.1. ARCHITECTURE DIAGRAM:

Fig.1. Block diagram of proposed system

Working process:

The general layout and functional elements of the renewable energy-integrated EV charging system are represented by the system architecture[14]. EV chargers, DC–DC converters with MPPT, a DC–AC three-phase inverter, hybrid energy storage (batteries and supercapacitors), renewable energy sources (wind turbines and solar PV), and the control and monitoring system make up this system[15]. To guarantee that energy is effectively captured, stored, and delivered while

preserving grid stability, each module works in unison. The architecture has a strong emphasis on modularity, which enables scalability and flexibility for future integration of EV loads or other renewable sources[16]. The core of the architecture is the control layer, which uses adaptive PI and PID controllers to control power flow, preserve DC bus voltage, and provide priority to key loads. Vehicle-to-grid (V2G) functionality is made possible by bidirectional inverters, and the hybrid storage system reduces temporary disruptions. The architecture guarantees a stable and sustainable charging infrastructure by maximizing the use of renewable energy, meeting EV charging demands dynamically, and minimizing grid stress.

4.2. FLOW DIAGRAM :

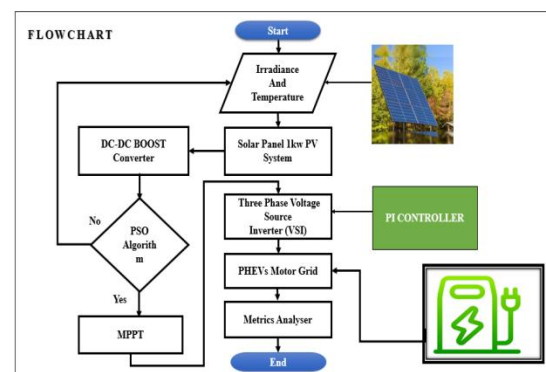


Fig.2. Flow chart diagram

The EV charging system's sequential functioning from energy generation to consumption is depicted in the flow diagram. Energy from renewable sources

is first gathered, and then voltage is regulated using DC–DC boost converters with MPPT. After then, energy is either stored in the hybrid supercapacitor-battery system or sent to the DC–AC inverter for EV charging and AC loads. To guarantee effective power distribution, the system continuously checks voltage, current, and state-of-charge. Control logic and decision-making procedures, such as transitioning between storage and direct load supply, managing unexpected demand spikes, or returning excess energy to the grid, are also depicted in the flow diagram[17]. It provides a visual roadmap of system operations, highlighting the relationships between energy generation, storage, EV charging, and grid integration. This ensures effective energy management and reliable performance under a range of load and generation scenarios.

4.3. ADVANTAGES:

- Equitable distribution of active power curtailment according to each prosumer's input.
- Effective overvoltage mitigation in networks with a high PV content.
- Adaptive and dynamic reaction to shifting PV generation circumstances and load.
- Lower power losses and increased overall system efficiency[18].
- Lower total harmonic distortion (THD) and improved voltage quality.

5. LITERATURE SURVEY:

1. Solar-powered grid-integrated charging stations with hybrid energy storage systems were proposed by Avinash Kumar Yadav, Anindya Bharatee, and Pravat Kumar Ray. A photovoltaic (PV) array and a hybrid energy storage system (HESS) that combines batteries and supercapacitors are incorporated in this solar-powered grid integrated charging station. Hybrid storage provides energy during both transient and steady stages; EV battery charging using a "stepwise constant current" control technique where charging current reduces as state-of-charge (SoC) increases[19]; and a boost converter (with MPPT utilizing P&O algorithm) interfaces PV to DC bus. Stepwise current charging lessens the strain on EV batteries and prevents overcharging; hybrid storage lowers transient effects and enhances steady-state performance;

2. PV and storage integration leverages renewable energy and lessens reliance on the grid; simulation (MATLAB/Simulink + OPAL-RT) demonstrates reliable operation under changing load/RES conditions. Dharmendra Kumar Dheer, Attuluri R. Vijay Babu, and Saleha Tabassum Described The article "Adaptive energy management strategy for sustainable xEV charging stations in hybrid microgrid architecture" was published in 2025. The

hybrid microgrid design used in this project combines solar PV, wind turbines, storage devices, and EV chargers [20]. An Adaptive Neuro-Fuzzy Inference System (ANFIS) controller-based energy management system is the main innovation. It dynamically optimizes power flow and storage utilization based on real-time conditions (generation, demand, SoC, load priority) under uncertainty and renewable variability. The ANFIS controller adaptively manages nonlinearities and uncertainties in renewable generation and EV demand; simulation results, according to the authors, show ~92% increase in energy efficiency and ~89% improvement in load-handling capacity compared to conventional methods; guarantees stable operation under variable weather and load conditions; enhances renewable utilization and avoids overtaxing storage or the grid.

6. IMPLEMENTATION OF METHODOLOGY:

6.1. Renewable Energy Resources (Wind Turbine and Solar PV) :

Sustainable EV charging solutions are based on renewable energy sources. This module uses wind turbines and solar photovoltaic (PV) panels to provide clean, green energy to the charging infrastructure. While wind turbines use electromagnetic induction to transform kinetic wind energy into electrical energy, solar PV uses the

photovoltaic effect to convert sunlight into DC electricity. Because both sources are sporadic, rigorous coordination is necessary to guarantee a steady power supply. Power electronic converters are used to interface these renewable sources with the system in order to maximize energy extraction. Environmental factors including temperature, wind speed, and irradiance affect PV and wind generation output[21].

In order to preserve system reliability, real-time monitoring and control techniques are crucial. This module lays the groundwork for effectively combining renewable energy with EV loads and storage. An EV charging station's integration of solar and wind power saves carbon emissions and lessens reliance on the main grid. Additionally, it enhances grid resiliency by supporting a decentralized energy generating strategy. The system can provide more dependable electricity for fluctuating EV charging demands by partially offsetting the intermittency of each of these two renewable energy sources.

6.2.DC–DC Converter with MPPT (Boost Converter): The DC bus of the EV charging system is connected to renewable energy sources via a DC–DC converter. This module uses a Boost Converter to raise the voltage from the wind turbine or

PV array to a level appropriate for charging and storing loads. The converter makes sure that energy produced from renewable sources is compatible with downstream components and used efficiently. The DC-DC converter is coupled with Maximum Power Point Tracking (MPPT) to continuously modify the PV array's or wind turbine's operating point. Regardless of changes in the environment, MPPT algorithms like Perturb and Observe (P&O) guarantee that the renewable source constantly runs at maximum efficiency.

This increases energy extraction and minimizes waste, which is especially crucial in situations where wind or sunshine fluctuates. The system's overall stability and efficiency are improved by this module. It keeps batteries from being overcharged and guarantees steady power supply to the DC bus by regulating voltage and current levels. In order to maximize the use of renewable energy for EV charging, the MPPT-enabled DC-DC converter serves as a link between the hybrid storage system and intermittent renewable power.

6.3: Hybrid Supercapacitor-Battery Management System (BMS):

Supercapacitors and batteries are used in the hybrid energy storage system to

balance power density and energy density. Supercapacitors manage quick transient loads and high power requirements, whereas batteries offer long-term energy storage appropriate for continuous EV charging. In order to maximize performance and extend battery life, the Battery Management System (BMS) keeps an eye on the voltage, health, and state-of-charge (SoC) of batteries. Supercapacitors lessen battery stress by providing instant power during abrupt load shifts or rapid EV charging events[22]. By regulating charging and discharging cycles and distributing power based on demand and SoC levels, the BMS guarantees coordinated functioning between batteries and supercapacitors. This preserves DC bus voltage stability, lowers energy loss, and increases system efficiency. The system can accommodate both short-term high-power needs and long-term energy demands by including hybrid storage.

Because it mitigates the effects of changing EV loads and sporadic renewable energy sources, this module is essential to grid stability. Additionally, it permits bidirectional power flow, which makes it possible to feed energy back into the grid when needed.

6.4. DC-AC Three-Phase Inverter: For grid integration and EV charging, the DC-AC inverter transforms DC power from

storage devices and renewable sources into AC power. To manage high-power applications, guarantee balanced AC output, and permit bidirectional power flow, a three-phase inverter is utilized. This module enables the system to communicate with other energy systems, support grid operations, and provide energy to AC loads.

Pulse-width modulation (PWM) techniques are used to manage the inverter's voltage, frequency, and current. Sophisticated control techniques minimize harmonics in the output waveform, preserve voltage stability, and guarantee grid synchronization. During times of high demand, the system's bidirectional capability enables it to either absorb extra grid energy or return stored energy to the grid[23]. In order to enable vehicle-to-grid (V2G) operation and incorporate renewable energy into the grid, this module is essential. The inverter guarantees compatibility with common EV chargers and electrical loads by effectively converting DC to AC. Ancillary services including voltage regulation, reactive power compensation, and grid support during disruptions are also supported.

6.5. Load Integration and EV Charging System: Power distribution between several EV chargers, auxiliary loads, and the grid supply is controlled by the load

integration module. It prioritizes important loads, keeps an eye on the demand for EV charging in real time, and manages the distribution of energy from storage systems and renewable sources. While preserving grid stability, this gadget makes sure EVs are charged effectively. Dynamic load profiles, which indicate different charging rates based on vehicle type and SoC, are used to simulate EV chargers. In order to prevent overload situations and lessen the strain that peak demand places on the grid, the module employs scheduling and energy management techniques to distribute power as efficiently as possible. Transient demands are satisfied without interfering with other loads thanks to integration with hybrid storage.

This module offers time-of-use optimization and demand response flexibility for smart charging. By ensuring that EV charging is in line with the availability and storage capacity of renewable generation, it lowers energy costs and maximizes sustainability. This module improves user happiness and system stability by efficiently handling load priorities.

6.6: Performance Analysis and Control:

The complete EV charging system must be regulated via control and performance

analysis to guarantee peak performance. DC bus voltage is maintained, current flow is controlled, and power is distributed among storage, renewable energy sources, and EV loads using adaptive controllers like PI and PID controllers. In order to react to changing circumstances, this module regularly checks system parameters[24]. To assess the efficacy of the system, performance indicators such as voltage sag/swell, harmonic distortion, total harmonic distortion (THD), power flow efficiency, and renewable energy consumption are examined. The control system can dynamically modify parameters to increase stability and dependability thanks to real-time data from sensors and measurement units. Additionally, this module facilitates simulation-based validation, offering insights into operational improvement and energy management tactics. It helps find possible enhancements, guarantees reliable performance, and directs the development of sustainable EV charging infrastructure by examining system behavior under various load and generation conditions.

7. RESULTS AND DISCUSSIONS:

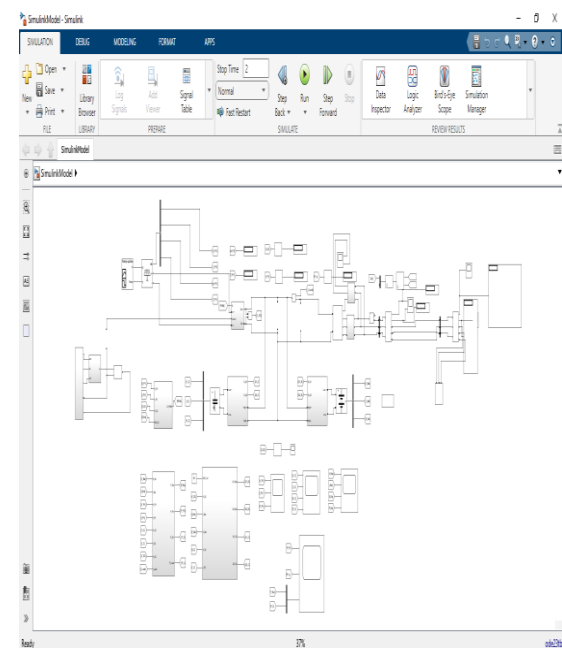


Fig.3. Simulink Model

The entire system simulation created in the MATLAB/Simulink environment is shown in this image. It depicts a sophisticated power electronics system that probably combines battery storage, wireless power transfer, and a renewable energy source (shown by the solar array block on the left). The graphic shows how power and data move through several subsystems, such as DC-DC converters, control loops (such PID controllers), and measurement blocks (scopes) that track voltage, current, and state-of-charge[22]. The connections demonstrate how the logic governs the hardware elements to control the charging procedure.

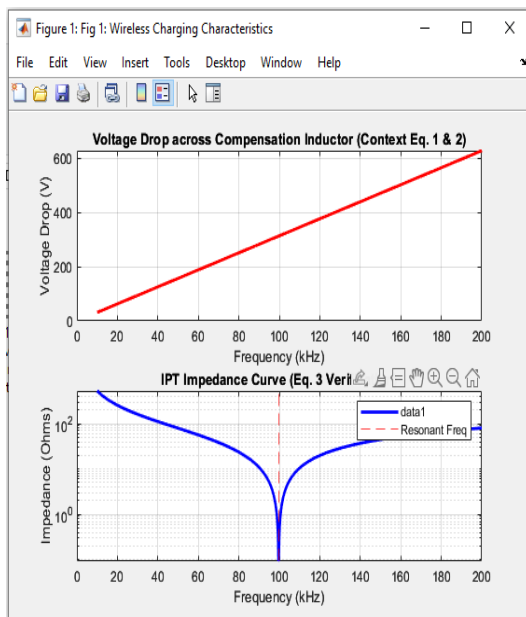


Fig.4. Wireless Charging Characteristics

The basic electrical behavior of the inductive power transfer (IPT) technology utilized for near-field wireless charging is depicted in this picture. An important consideration for choosing component insulation ratings is the voltage drop across the compensation inductor, which is plotted in the top graph and shows a linear increase as frequency climbs. The impedance curve of the resonant circuit is shown in the bottom graph[23]; the "V" shape denotes that the system is tuned to a resonant frequency of precisely 100 kHz, when the impedance reduces to its minimal value, enabling maximum current flow and effective power transmission.



Fig.5. Far-Field Wireless Charging

Instead of using inductive coupling, this collection of graphs examines a long-range wireless power transmission system that is probably based on optical (laser) or microwave technology. The top two charts illustrate the "Inverse Square Law," which states that as the distance between the transmitter and receiver rises from 0 to 5 meters, both received power and transfer efficiency sharply decline[24]. The "efficiency chain" is broken down in the bottom bar chart, which shows how much energy is lost at each step (Source, Laser, Beam, Atmosphere, PV, Converter), leading to a low overall system efficiency (the red bar) of about 20%.

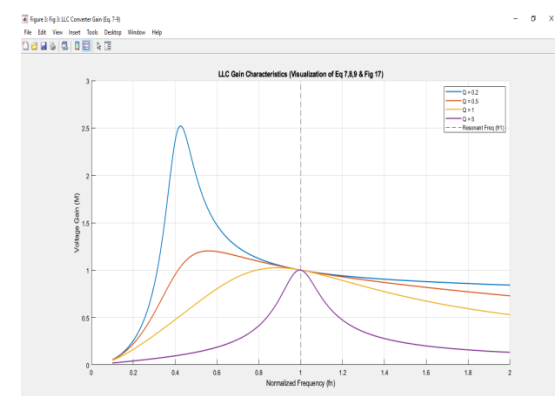


Fig.6. LLC Converter Gain

The frequency response of an LLC resonant converter, a circuit architecture well-liked for its high efficiency and soft-switching capabilities, is shown in this plot. Voltage Gain (MM) is plotted against Normalized Frequency (f_{nfn}) on the graph for a range of Quality Factors (QQ), which correspond to distinct load scenarios. The curves show that the curves meet close to the resonant frequency ($f_n=1f_n=1$), indicating a stable working point where the gain is predictable regardless of load variations, and that the converter boosts gain (Voltage $>1>1$) at lower frequencies (blue peak).

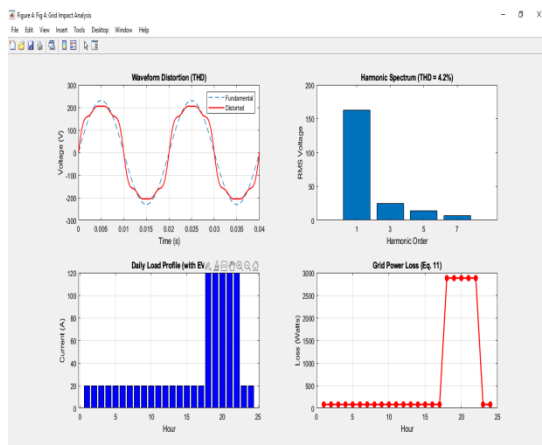


Fig.7. Grid Impact Analysis

This chart assesses the impact on the electrical utility grid of EV charging's high power demand. A distorted voltage waveform and a harmonic spectrum with third, fifth, and seventh harmonics that contribute to total harmonic distortion (THD) are displayed in the top two panels, which concentrate on power quality. The temporal impact is depicted in the bottom

panels: the "Daily Load Profile" displays a significant surge in current demand between 18:00 and 22:00 hours (probably when EVs plug in after work), which is directly correlated with a dramatic increase in "Grid Power Loss" during that particular time window.

8.CONCLUSION:

The suggested hybrid energy storage and renewable energy-integrated EV charging system shows great promise for resolving the issues related to growing EV adoption. The system efficiently handles variable energy generation, high transient loads, and dynamic EV charging demands by integrating solar PV, wind turbines, hybrid storage devices (batteries and supercapacitors), and bidirectional inverters. Improved voltage stability, decreased total harmonic distortion (THD), effective energy use, and increased system reliability are all demonstrated by simulation findings. Its technical and operational viability is highlighted by the modular and adaptive control design, which guarantees scalability, operational flexibility, and integration with the current power system.

Overall, the study shows that hybrid storage and sophisticated control techniques can maximize the use of renewable energy sources while improving

grid stability. The project reduces reliance on the grid and promotes environmental sustainability by offering a sustainable and effective solution for contemporary EV charging infrastructure. The study provides a solid basis for creating durable, intelligent, and environmentally responsible EV charging systems that can satisfy the energy needs of transportation in the future.

9.FUTURE ENCHANCEMENT:

Future improvements to this system might concentrate on incorporating more renewable energy sources, like biomass or small-scale hydro, to further lessen reliance on the grid and improve sustainability. To optimize real-time energy distribution, predict EV charging trends, and boost system efficiency, sophisticated energy management techniques, such as machine learning-based predictive controllers, could be put into practice. More intelligent, adaptable, and autonomous operating under fluctuating generation and load situations would be made possible by these advancements. Additionally, the system might make greater use of vehicle-to-grid (V2G) technology, which would enable EVs to both consume and return stored energy to the grid during moments of high demand. This would improve grid stability, offer supplementary services, and

generate possible income. Next-generation smart charging infrastructure may be made possible by the integration of smart metering, IoT-based monitoring, and cloud-based analytics. This might also allow for remote management, predictive maintenance, and real-time performance optimization.

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