

Integration of EV Charging with Renewable Energy

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Abstract

The integration of electric vehicle (EV) charging with renewable energy (RE) sources presents a promising path toward sustainable transportation and energy use. As the global adoption of EVs accelerates, traditional charging methods relying on fossil fuels pose challenges to achieving environmental goals. This paper explores the potential of integrating RE sources, such as solar, wind, and hydroelectric power, with EV charging infrastructure to reduce greenhouse gas emissions and optimize energy management. Key topics covered include technological advancements in smart charging infrastructure, bidirectional charging (V2G), and energy storage solutions that enable seamless integration with intermittent RE sources. The paper also addresses the critical challenges in this integration, such as the variability of RE generation, the need for robust grid infrastructure, and the economic implications of large-scale implementation. Various strategies to overcome these barriers are discussed, including smart grid evolution, hybrid energy systems, and intelligent energy management. Through a review of current technologies, case studies, and future trends, this research aims to provide a comprehensive understanding of the opportunities and limitations in using RE for EV charging, highlighting its crucial role in the transition toward a greener energy landscape.

Keywords: Solar panel, BMS, IOT, EV charging station integration, renewables, EV charging, sustainability, smart charging, bidirectional, storage, variability, grid, economic, hybrid systems, management, technologies, trends, challenges

INTRODUCTION

Although the popularity of electric vehicles (EVs) has greatly reduced the carbon footprint of transportation, the environmental advantages of EVs primarily rely on the source of the electricity used for charging. With most current grids relying on fossil-fuel-based power generation, there remains a critical need to integrate renewable energy (RE) sources such as solar, wind, and hydroelectric power into the EV charging infrastructure. As countries aim to meet sustainability targets, the deployment of renewable energy for EV charging has become a priority, not only to reduce greenhouse gas emissions but also to enhance energy security and independence [1].

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The use of clean energy sources for powering electric vehicles faces various hurdles, particularly because of the unpredictable behavior of sources such as wind and solar power. This fluctuation can strain the power infrastructure, demanding sophisticated charging tactics and energy storage systems to adequately balance supply and demand. For example, the implementation of smart charging approaches such as network charging and shift charging can optimize the use of excess RE during off-peak periods, alleviate grid stress, and lower operational costs [2].

Programming programs, such as Austin Energy's Plug-in Everywhere Network, allow customers to

charge their EVs using wind energy, providing a model for integrating RE into the EV charging ecosystem [3].

Moreover, advancements in energy management and smart grid technologies have made it possible to synchronize EV charging with periods of high RE generation, thereby improving grid stability and energy efficiency. Through initiatives such as time-of-use (ToU) rates and managed charging programs, utilities can encourage consumers to charge their vehicles when RE availability is highest, further supporting the transition to a low-carbon energy system [4].

This paper explores the current technologies, challenges, and strategies associated with integrating RE into the EV charging infrastructure, aiming to provide insights into achieving sustainable and efficient mobility [5].

EXISTING RENEWABLE ENERGY SOURCES FOR EV CHARGING

Integrating RE sources with EV charging is a promising path toward sustainable transportation. Several RE sources can sustain EV charging construction, each with its advantages and drawbacks. The primary sources considered for integration are solar, wind, hydro, and biomass energies [6].

Solar Energy

Solar photovoltaic (PV) systems are widely used because of their ease of installation, technical maturity, and relatively low maintenance. Solar energy can be directly utilized for EV charging, particularly during daylight hours. However, its intermittent nature provides obstacles, as the production of electricity fluctuates according to weather conditions and the time of day. Solar power can be combined with energy storage devices to store extra electricity for use when the solar generation is limited. Various initiatives, such as solar-to-EV pilot projects, have demonstrated successful integration into residential and commercial applications, highlighting the potential for widespread adoption [7].

Wind Energy

Wind power is another viable option for EV charging with significant potential in regions where wind resources are abundant. The fundamental feature of wind electricity is its potential to provide power during the night and enhance solar energy production. However, wind energy shares the challenge of intermittency and can be affected by weather patterns, making the grid integration complex. Programs like the plug-in network in Austin demonstrates the feasibility of using wind energy for EV charging, offering customers the ability to source 100% of their electricity from renewable sources such as wind [8].

Hydropower

Although not intermittent, such as solar or wind power, hydropower can support EV charging by providing a stable and consistent energy supply. Its high-power capacity and technological maturity make it an essential component of renewable integration strategies. However, environmental concerns such as aquatic ecosystem disruption and secondary emissions during dam construction need to be considered [9].

Biomass

Biomass energy derived from organic materials offers a more consistent energy supply than solar and wind energy. Hybrid renewable-energy-based EV charging systems can be used as an additional source. Although biomass is a renewable resource, the source material and burning method have different effects on the environment [10].

Challenges in Integration

There are several obstacles to using solar and wind energy directly for EV charging owing to their sporadic nature. Strategies to address these challenges include energy storage solutions, smart grid

technologies, and hybrid systems that combine multiple RE sources. Advanced energy management techniques, such as shift charging and managed charging, can optimize the use of excess RE, thereby ensuring a more balanced and reliable energy supply for EVs [11]. The integration of these renewable sources of information, along with breakthroughs in energy conservation and smart grid technological advances, can significantly assist the sustainable EV recharging infrastructure [12].

TECHNOLOGICAL INFRASTRUCTURE FOR EV AND RE INTEGRATION

Connecting EV charging facilities with RE demands sophisticated infrastructure designed to handle the intermittent nature of renewable power sources and maintain efficient transmission of energy between EVs, electrical systems, and energy storage mechanisms.

Several key components form the foundation of this infrastructure, including smart charging systems, energy storage solutions, and power converters, all of which play pivotal roles in enabling seamless integration between EV charging and RE sources [13].

Smart Charging Infrastructure

The term ‘smart charging’ describes the clever control of EV charging to optimize the use of RE sources and balance grid loads. Unidirectional (V1G) and bidirectional (V2G) charging are the two main categories of smart charging technologies [14].

V1G Charging: In V1G systems, EVs charge only in one direction, from the grid to the vehicle, allowing for intelligent control of when and how fast an EV charges, based on grid demand and RE availability. This system can optimize charging schedules to match times when RE generation is at its peak, such as midday for solar power or during the night when wind energy generation is high. Managed through demand response programs, the V1G can reduce charging costs and relieve grid stress by shifting EV charging away from peak hours [15].

V2G Charging: On the other hand, V2G (Vehicle-to-Grid) systems allow energy to flow in both ways so that EVs can both draw power from the grid and return stored energy to the grid when demand is high or when RE production is low. This transforms EVs into mobile energy storage units, which helps stabilize the grid and increases the employment of intermittent sustainable energy sources of information. V2G technologies enable the greater incorporation of renewables by allowing EVs to respond as a buffer, storing excess RE, and sending it when needed [16].

This significantly improves grid flexibility and resilience, while also offering EV owners the potential to earn income by selling surplus energy back to the grid. V1G and V2G technologies are foundational to the future of renewable-enabled smart grids as they ensure more efficient use of available RE and mitigate grid congestion caused by large-scale EV adoption [17].

Energy Storage Technologies

Energy storage is crucial for ensuring that RE can meet the variable demand of EV charging, especially because RE sources such as solar and wind are intermittent by nature. Energy storage solutions help store excess RE generated during periods of high availability and release it during times of peak demand when renewable generation may be low [18].

Battery Energy Storage Systems

Battery systems, particularly lithium-ion batteries (LIBs), are among the most widely used solutions for storing RE for EV charging. Battery storage can be installed at many scales, ranging from modest home systems to massive utility-scale arrays. These systems store the extra energy created during periods of strong renewable output, such as bright or windy days, and release it when the grid demands additional dominance, such as during cloudy or calm periods. Batteries can be co-located with EV charging stations, particularly in commercial or high-traffic areas, to provide a local buffer that reduces

strain on the power grid [19]. Battery storage can also help balance the grid by absorbing excess RE during low-demand periods and supplying energy during peak demands, which is essential for grid reliability and RE integration.

Supercapacitors

Supercapacitors, which are not as widely used as batteries, offer another energy storage option. They are characterized by their ability to store and release energy quickly, making them ideal for applications that require rapid energy dispatch, such as fast-charging EV stations. Although they have a lower energy density than batteries, supercapacitors can complement battery systems by handling short-term energy fluctuations, thus extending the battery life and improving the overall energy management efficiency [20]. Supercapacitors are also advantageous in applications where frequent charge-discharge cycles are required, as they offer longer lifespans than traditional batteries.

Hybrid Energy Storage Systems

A developing trend in energy storage involves the mixing of several storage solutions into hybrid arrangements. Hybrid systems, such as combining batteries and supercapacitors, leverage the high energy density of batteries with the fast response times of supercapacitors, providing both long-term storage and rapid energy dispatch capabilities. This combination is particularly useful for EV charging networks, where fluctuations in both demand and RE generation must be balanced [21].

Hybrid energy storage systems can improve the efficiency of RE use by smoothing out the energy supply and reducing the load on the grid during peak charging periods. Additionally, they enable the more reliable use of RE for EV charging stations, especially in off-grid or remote locations where grid connectivity may be limited [22].

Power Converters and Grid Integration Technologies

Power converters play a critical role in facilitating the smooth integration of RE sources with EV charging. As RE sources often generate direct current (DC) power while most grids operate on alternating current (AC), efficient conversion technologies are necessary to bridge this gap. Furthermore, EVs rely on DC power for charging, necessitating conversion at multiple points in the energy flow from renewable generation to vehicles [23].

1. *AC/DC Converters:* AC/DC converters are essential for converting alternating current from the grid or renewable sources (such as wind or solar) into direct current used for EV batteries. These converters are integral to both the on-grid and off-grid charging setups. In on-grid applications, AC/DC converters ensure that RE can be efficiently stored in EV batteries, whereas in off-grid applications, they enable direct renewable-to-EV charging [24].
2. *DC Fast Chargers:* DC fast chargers are a sophisticated technology that enables lightning-fast charging of EVs by supplying DC power directly to the battery, skipping the need for onboard conversion. These chargers are perfect for public and commercial charging stations because they can quickly offer large amounts of electricity. As DC fast charging is becoming increasingly popular, it is essential to align this infrastructure with RE generation to ensure efficient energy flow and minimize reliance on fossil-fuel-based grid power [25].
3. *Bidirectional Inverters:* In V2G systems, bidirectional inverters enable energy to flow in both directions between the grid and EV battery. These inverters are vital for facilitating the return of stored energy from EVs to the grid during peak demand periods or when RE production is low. Additionally, they encourage the use of EVs as mobile energy storage devices, which can help stabilize the grid by supplying electricity when there is a shortage.
4. *Intelligent Grid Integration Solutions:* To manage the complex interaction between RE sources, storage systems, and EVs, intelligent grid integration technologies, such as smart meters, demand response systems, and grid management software, are essential. Real-time engagements between EVs, charging places of confinement, and the network are made conceivable by these devices, enabling schedules that are adjusted based on grid demand and the availability of RE [26].

The use of real-time data and predictive analytics can significantly enhance the efficiency of RE integration by forecasting periods of high RE generation and adjusting the EV charging accordingly. In addition to reducing expenses, this strategy increases the overall environmental sustainability of the energy system [27].

The technological infrastructure for integrating RE with EV charging is rapidly evolving with innovations in smart charging, energy storage, and power conversion leading the way. As the adoption of EVs continues to grow, the development and deployment of these technologies will be critical for ensuring that RE can meet the demands of large-scale EV charging. These technologies will be essential for the shift to a low-carbon, sustainable transport system because they will ensure efficient energy flow and overcome the intermittent nature of RE streams [28].

RENEWABLE ENERGY-ENABLED SMART CHARGING APPROACHES

As RE sources, such as solar and wind, have become increasingly integrated with EV charging systems, the need for smart charging approaches has become paramount. Smart charging refers to the strategic management of the EV charging processes in response to energy availability, grid conditions, and user preferences. These approaches ensure that EVs are charged when RE supply is abundant, reducing reliance on fossil-fuel-powered electricity and alleviating stress on the power grid [29].

Smart charging can be achieved through several key mechanisms, including network charging, shift charging, managed charging, and demand response strategies. By utilizing RE more efficiently and aligning EV charging with periods of high renewable generation, smart charging can significantly contribute to decarbonization efforts and improve grid stability [30].

Network Charging

Network charging refers to the dynamic coordination of charging schedules across a network of charging stations, optimizing the energy flow based on real-time data from the grid and RE sources. This system works by aggregating data from multiple charging points and intelligently distributing the energy load across the network [31]. In regions where RE generation is high, such as areas with extensive solar or wind infrastructure, network charging ensures that EVs are primarily charged when RE is available.

This approach not only reduces the carbon footprint of EV charging but also alleviates the demand on the grid during peak hours by utilizing energy during off-peak times when RE is more abundant [32].

For example, in cities with large solar installations, network charging can prioritize charging EVs at midday when solar energy is at its peak. Similarly, in regions with high wind energy generation, charging can be shifted to nighttime when wind production is typically stronger. This reduces the overall energy cost and minimizes the use of fossil-fuel-derived grid electricity [33].

Shift Charging

Shift charging refers to the strategic shifting of EV charging times to periods when RE is readily available or grid demand is low. This method is particularly effective for reducing the peak demand stress on the grid and increasing the utilization of RE. Through shift charging, EV owners can charge their vehicles at times when RE sources generate surplus power [34].

Time-of-use tariffs, which encourage EV owners to charge their cars during off-peak hours or when energy from renewable source production is at its height, are one of the main technologies enabling shift charging. These rates typically involve lower electricity prices during periods of low demand, which encourages users to shift their charging activities accordingly. ToU pricing models have been adopted in many regions to promote sustainable charging behaviors among EV owners while lowering grid operational costs [35].

For instance, ToU rates can encourage EV owners to charge their vehicles midday when solar energy is plentiful, or at night when wind energy is in surplus. This helps reduce reliance on conventional fossil-fuel-based electricity during peak hours and maximizes the use of clean energy.

Shift charging can also be enhanced by intelligent algorithms that automatically schedule charging based on the predicted RE generation and grid demand. These algorithms can dynamically adjust charging times in real time to optimize both energy use and costs, making shift charging an integral part of the smart grid ecosystem [36].

Managed Charging

Managed charging goes beyond simply shifting the charging times by actively controlling the rate and duration of EV charging based on real-time grid conditions and RE availability. This approach is crucial for preventing grid overloads during peak demand periods and ensuring that EV charging does not destabilize the grid.

In managed charging systems, charging is dynamically adjusted to match the RE supply. For example, when solar or wind energy generation is high, managed charging can increase the charging rate of EVs to absorb the surplus energy. Conversely, during periods of low RE production, charging rates can be reduced or postponed to avoid drawing excessive power from nonrenewable sources [37].

This real-time control of EV charging helps balance the grid while maximizing the use of RE. Managed charging systems also allow grid operators to implement demand response programs, in which EV charging is temporarily reduced during grid emergencies or high demand periods to avoid blackouts or grid instability. In return, EV owners may receive financial incentives or lower charging costs for participating in demand response programs [38].

Managed charging is particularly important in scenarios where RE generation is unpredictable, such as in regions with fluctuating wind or solar output. Managed charging guarantees more reliable and effective integration of energy from renewable sources into the grid by coordinating EV charging schedules with RE production.

Demand Response and Vehicle-to-Grid (V2G) Systems

Demand response programs are designed to encourage consumers to adjust their energy usage based on grid conditions, and EVs are increasingly becoming a part of these programs. Grid managers can use demand responses to ask EV owners to postpone or cut back on charging when demand is high or RE supplies are few. In exchange, EV owners receive financial rewards or reduced electricity rates [39].

By enabling EVs to send power back into the electrical system during periods of high demand or electricity shortages, vehicle-to-grid (V2G) systems go one step further. With V2G, EV batteries have become mobile energy storage units that can discharge stored RE into the grid when needed. This improves the overall efficiency of RE sources while stabilizing the system. When it comes to balancing intermittent energy from environmentally friendly sources, such as solar and wind, V2G systems are especially useful [40].

For example, when solar energy generation drops in the evening, EVs can supply power back to the grid from the energy they store during the day. Similarly, EVs can provide power during nighttime demand peaks when wind energy generation slows down. This bidirectional energy flow transforms EVs into key assets for RE integration and grid management.

Financial incentives for V2G participation are significant, as EV owners can sell stored energy back to the grid at higher rates during peak periods, providing both grid support and personal savings. Furthermore, V2G technology will become increasingly crucial to the grid's ability to integrate RE sources as it develops [41].

Case Studies: Real-World Implementations

Several real-world projects have successfully demonstrated the potential of renewable-energy-enabled smart charging approaches.

- *Austin Energy's Plug-in Everywhere Network* is an excellent example of how smart charging can be combined with RE. This initiative allows EV owners to charge their vehicles using 100% of the RE from wind power. By providing flat-rate charging access across a network of public charging stations, Austin Energy has effectively integrated RE into its EV infrastructure, promoting clean transportation options and reducing grid strain.
- *Tesla's Smart Solar Charging Project* was another notable case study. Tesla has developed a solar-powered charging system in which solar panels charge power wall battery storage units, which then provide power to EV charging stations. This system ensures that EVs are charged directly from renewable sources, reducing the dependence on grid power and ensuring a cleaner charging process.

Both examples illustrate how smart charging strategies, coupled with RE, can promote sustainability while ensuring grid stability. Renewable energy-enabled smart charging approaches are transforming the integration of vehicles are integrated into the energy ecosystem. By leveraging network charging, shift charging, managed charging, demand response, and V2G systems, it is possible to optimize the use of RE for EV charging, while enhancing grid stability and reducing costs. These approaches not only help to balance energy supply and demand but also support the broader transition toward sustainable, low-carbon transportation. As RE generation increases, smart charging will become an essential tool for managing the interaction between EVs and grids.

OPPORTUNITIES AND CHALLENGES

Electric vehicle charging combined with RE has significant potential for optimizing energy use, lowering greenhouse gas emissions, and supporting the global transition to sustainable transportation.

However, it also brings several technical, economic, and infrastructural challenges that must be addressed to ensure its widespread adoption and reliability. This section explores the key opportunities presented by this integration, along with the significant challenges that need to be overcome.

Opportunities

The increasing use of EVs and their integration with RE sources offer several notable opportunities, contributing to environmental goals, economic benefits, and advancements in energy management technologies.

Reduced Greenhouse Gas Emissions

One of the primary opportunities to integrate RE with EV charging is to drastically reduce greenhouse gas (GHG) emissions. The environmental advantages of EVs are greatly increased when electricity is obtained from RE sources, such as solar, wind, and hydro. Conventional internal combustion engine (ICE) vehicles contribute heavily to carbon emissions, and while EVs have zero tailpipe emissions, emissions from electricity generation still play a role in their total carbon footprint. By pairing EVs with RE sources, their operation can be nearly emission-free, thus making a profound contribution to decarbonizing the transportation sector.

Grid Decentralization and Flexibility

The integration of EVs into the grid through smart charging and vehicle-to-grid (V2G) systems enhances the flexibility of energy distribution and supports the decentralization of power generation. EVs can act as mobile energy storage devices with V2G technology, returning energy to the grid in times of emergency or high energy demand. This allows for more efficient grid management, as distributed energy resources (DERs) such as EVs help smooth demand spikes, balance energy loads, and reduce the need for additional fossil-fuel-based peaker plants.

In regions with high RE penetration, EVs can help absorb excess generation during overproduction, such as when solar power peaks in the afternoon. Conversely, EVs can supply stored energy back to the grid when renewable generation is low, thereby contributing to grid stability.

1. *Economic Savings and Revenue Generation:* Renewable energy-powered EV charging systems present economic advantages to both consumers and grid operators. ToU pricing models and demand response programs allow EV owners to charge their vehicles at lower rates during off-peak hours when RE generation is typically more abundant. This reduces the overall cost of electricity for consumers while promoting the more efficient use of RE. Additionally, by selling their stored energy back to the grid during times of high demand, EV owners participating in V2G schemes can profit. This creates an economic incentive for EV owners to participate in grid stabilization efforts while also allowing grid operators to avoid the high costs of ramping up fossil-fuel power plants during peak hours.
2. *Support for RE:* Integration of RE sources such as solar and wind is intermittent, and the integration of EVs with RE supports their wider adoption by providing a flexible load that can absorb excess energy generation. EVs can act as a demand sink during times of surplus renewable generation, helping to avoid the curtailment of RE. This ensures that more RE is utilized, even during periods when traditional demand does not match the supply. Grid operators can improve the implementation of RE in the energy mix and eventually aid in the decarbonization of the electrical grid by scheduling EV charging during times when the RE output is at its highest.

Challenges

Despite the abundance of options, several obstacles must be overcome to fully realize the potential of combining RE with EV charging. To overcome these obstacles, which cut across the technical, financial, and regulatory spheres, concerted efforts are required.

Infrastructure Costs

A significant challenge in integrating RE with EV charging is the high infrastructure costs associated with deploying widespread renewable energy-powered charging stations. It costs a lot of money to install solar panels, wind turbines, and other renewable energy-producing equipment close to EV charging stations. Additionally, integrating these renewable systems with energy storage solutions, such as batteries or supercapacitors, to manage intermittent supply can further increase the costs. Moreover, upgrading the grid infrastructure to support the large-scale deployment of EVs, smart charging systems, and V2G technologies requires significant investment. This includes enhancing transmission and distribution networks to handle increased loads and installing advanced grid management systems to enable real-time communication between EVs, charging stations, and the grid. Intermittency and grid stability are one of the biggest obstacles to integrating RE with EV charging is the unpredictability of renewable energy sources such as solar and wind.

Solar Energy

Solar energy generation peaks during the day, while wind energy is often strongest at night, yet EV charging demand can occur at various times of the day, including peak electricity consumption periods. To maintain grid stability in the face of this imbalance between energy supply and demand, advanced grid management techniques are required. Furthermore, the unpredictable nature of RE generation can lead to grid instability if not managed properly. Without sufficient energy storage or demand response mechanisms, the fluctuating output of renewable sources can cause imbalances in the power grid, leading to potential blackouts or the need for backup generation from fossil-fuel-based sources.

Energy Storage Limitations

While energy storage technologies, such as batteries and supercapacitors, are critical for balancing the intermittent supply of RE, they are still expensive and face limitations in terms of energy density, cost, and lifespan. The high cost of energy storage systems can render renewable energy-powered EV charging economically challenging, particularly in areas with limited access to affordable storage solutions. Additionally, energy storage systems are not yet widespread enough to support the large-

scale deployment of renewable-energy-powered charging infrastructures. Without sufficient storage capacity, grid operators may struggle to align EV charging with RE generation, particularly during periods of low production or high demand.

Regulatory and Policy Barriers

The regulatory and policy environment also poses challenges for the integration of RE with EV charging. In many regions, outdated energy policies and regulations do not fully accommodate the deployment of smart charging systems, V2G technologies, or decentralized RE generation. For example, in some regions, EV owners may face regulatory barriers to selling electricity back to the grid through V2G systems, limiting their ability to participate in demand response programs. Furthermore, the absence of uniform laws in various areas may result in disparities between the management of EV integration and RE. Developing consistent policies that encourage the deployment of renewable-powered EV charging infrastructure and provide financial incentives for smart charging and V2G participation are essential for overcoming these barriers.

Strategies to Overcome Challenges

Several tactics can be used to overcome these issues:

1. *Hybrid Energy Systems:* Hybrid energy systems that combine RE with conventional energy sources can provide a more reliable and flexible solution for EV charging. For example, solar-powered EV charging stations can be supplemented with energy from the grid during periods of low sunlight while also utilizing battery storage to store excess energy for later use. This hybrid approach helps mitigate the intermittency of RE while ensuring a continuous power supply for EV charging.
2. *Intelligent Energy Management Systems:* The development and deployment of intelligent energy management systems are crucial for optimizing the integration of RE with EV charging. Grid operators may dynamically modify charging schedules and rates owing to these systems, which forecast RE production and EV charging demand using real-time data, predictive analytics, and machine-learning technologies.
3. By aligning EV charging with RE availability, intelligent energy management systems can reduce grid strain and enhance the overall efficiency of the energy system.
4. *Grid Renovation and Expansion:* To support the large-scale integration of EVs and RE, grid infrastructure must be renovated and expanded. This includes upgrading transmission and distribution networks, enhancing grid resilience to accommodate intermittent RE sources, and deploying advanced communication technologies to enable real-time interactions between EVs, charging stations, and the grid. Owing to these infrastructural upgrades, the grid will be better equipped to manage the rising electricity demand and facilitate the incorporation of RE.
5. *Reforming Policies and Regulations:* Legislators must enact laws to encourage EV charging and RE absorption. This includes creating incentives for the deployment of renewable-powered charging infrastructure, encouraging participation in demand response programs, and removing barriers to V2G and decentralized energy generation. Governments can accelerate the shift to sustainable energy and transport systems by creating a supportive regulatory framework.

FUTURE DIRECTIONS

The future of environmentally friendly transportation and energy systems will be shaped by a number of new developments and trends, such as the integration of RE and EV charging continues to advance.

These future directions involve advancements in smart grids, wireless charging, energy storage, and bidirectional energy transfer technologies, as well as new policy frameworks and infrastructure developments. To create a more robust and sustainable energy ecosystem, this section examines the major areas in which additional technological and strategic advancement is anticipated.

Evolution of Smart Grids and Dynamic Energy Management

Smart Grids

The next evolution of the power grid will involve the widespread implementation of smart grids, which are essential for managing the increasing demand for EVs and maximizing the use of RE. Smart grids utilize advanced communication technologies, data analytics, and automation to optimize the flow of electricity between power generation sources, storage systems, and consumers, including EVs.

Real-time energy management will be made possible by smart grids in the future, enabling grid managers to balance supply and demand dynamically. By integrating advanced metering infrastructure (AMI) with demand response programs, smart grids can efficiently manage fluctuations in RE generation, ensuring that EVs are charged during periods of high renewable output and that energy demand is reduced during peak periods. This real-time balancing of energy supply and demand will be critical as the number of EVs on the road continues to grow, particularly in areas with high penetration of intermittent RE sources, such as wind and solar.

Smart grids will also empower individuals by giving them more control over their charging habits and providing comprehensive insights into their energy usage trends. Through smartphone apps and other digital interfaces, EV owners can optimize their charging schedules to take advantage of lower electricity rates or higher RE availability. This level of consumer engagement further enhances the integration of RE into the transportation sector.

Wireless Charging Technologies and Urban Mobility

One of the most promising future directions in the EV charging space is the development of wireless charging technologies, which will significantly enhance the convenience and accessibility for EV users. Without the use of physical cords or connectors, wireless charging, which is sometimes referred to as inductive charging, transfers energy from a charging station to an EV battery using electromagnetic fields. Wireless charging can be used in a variety of locations, such as public spaces, companies, homes, parking lots, and shopping centers. This technology will make it easier for EV owners to charge their vehicles throughout the day without requiring manual plugs. As technology advances, wireless charging can be integrated into roadways, allowing EVs to charge while driving, which reduces the need for large stationary battery packs and enables continuous energy flow.

Dynamic Wireless Charging

A particularly exciting innovation is dynamic wireless charging (DWC), in which EVs can charge while in motion. A DWC involves embedding wireless charging infrastructure into roads, allowing EVs to draw power as they drive. This would drastically reduce the need for large onboard batteries and eliminate range anxiety, as vehicles can maintain a constant state of charge without needing to stop at traditional charging stations. Such systems could be especially beneficial for public transportation systems and long-haul trucking, where minimizing the downtime for charging is critical.

Although still in the early stages of development, wireless and DWC technologies represent a significant leap forward in making EV charging more accessible and integrated into everyday life. These systems can also reduce the physical footprint of charging stations in urban environments, helping to alleviate space constraints in densely populated areas.

Vehicle-to-Everything Technologies

Vehicle-to-everything (V2X) technologies represent a broader expansion of bidirectional energy transfer than the traditional vehicle-to-grid (V2G) concept. In V2X systems, EVs are capable of sharing energy not only with the grid but also with homes, buildings, and other devices. This transforms EVs into the integral components of a broader energy ecosystem.

Vehicle-to-Home

A key aspect of V2X is Vehicle-to-Home (V2H), where EVs can supply power to homes during outages or periods of high electricity prices. With V2H, EV owners can use their vehicles as backup generators, thereby providing essential electricity to their homes during emergencies. This not only increases energy resilience for households but also enhances the overall efficiency of the energy system by utilizing stored energy during times of peak demand or when RE generation is low.

Vehicle-to-Building

Another promising application is vehicle-to-building (V2B), where EVs interact with commercial or industrial buildings to provide power during peak hours, thereby reducing the building's demand on the grid. Businesses, particularly those involved in demand response initiatives, can save a significant amount of money. By coordinating energy flows between EVs and buildings, V2B systems can help stabilize local grids and contribute to overall grid resilience.

V2X for Smart Cities As cities become smarter and more interconnected, V2X technologies will play a crucial role in their development of smart cities, where EVs, RE sources, and smart infrastructure work together to create a dynamic, efficient, and sustainable urban environment.

In a V2X-enabled smart city, EVs interact with the grid, buildings, and other infrastructure to optimize energy flows, reduce carbon footprints, and enhance energy reliability. V2X will be a cornerstone of the future energy ecosystem, enabling the more efficient use of RE and transforming EVs from simple transportation devices into active participants in energy markets.

Advances in Energy Storage and Battery Technology

The future success of integrating RE with EV charging depends heavily on advancements in energy storage technologies. To solve the intermittent nature of RE sources and guarantee that there is sufficient energy to meet the demand for EV charging, energy storage devices are crucial.

Next-Generation Batteries: Significant progress has been made in the development of next-generation batteries, such as solid-state batteries and lithium-sulfur (Li-S) batteries, which promise higher energy densities, longer lifespans, and faster charging times than current LIBs. These advancements will play a key role in reducing the cost and increasing the performance of energy storage systems, making them more viable for large-scale deployment along with RE generation.

Grid-Scale Energy Storage: In addition to improving EV battery technology, advancements in grid-scale energy storage systems are critical for supporting RE integration. Techniques, such as flow rechargeable batteries, pumped hydroelectric storage, and compressed air energy storage (CAES), enable long-duration storage methods that can capture surplus RE through periods of high supply and distribute it when consumption is high or when the availability of RE is low.

These large-scale storage systems will complement distributed storage solutions such as home batteries and EVs, creating a more resilient and flexible energy system. As the demand for EVs and RE continues to grow, the development of cost-effective, high-capacity energy storage systems is essential to ensure that clean energy can meet future electricity demands.

Policy and Regulatory Frameworks

The widespread adoption of renewable energy-powered EV charging will also require supportive policies and regulatory frameworks to encourage investment in new technologies and infrastructure. Governments and regulatory bodies need to implement policies that facilitate the integration of EVs with RE, promote the deployment of smart grids, and support the development of energy storage solutions.

Incentives for Smart Charging and V2G Participation Governments can provide financial incentives for EV owners to participate in smart charging and V2G programs. These incentives include reduced electricity rates, tax credits, and direct financial rewards for EV owners who allow their vehicles to be used as energy storage devices for the grid. By encouraging widespread participation, policymakers can help optimize grid efficiency and increase the use of RE.

Standardization and Interoperability: Another key area for regulatory development is the standardization of charging infrastructure and V2G technologies. Standardization is crucial for ensuring the interoperability between different EV models, charging networks, and grid systems, making it easier for EV owners to access renewable energy-powered charging stations. Harmonized standards also support the broader integration of V2X technologies, enabling seamless communication between EVs, the grid, and other energy assets.

Global Collaboration and Research Investment Finally, governments must invest in research and development (R&D) and encourage global collaboration to accelerate the advancement of RE technologies, energy storage solutions, and smart grid systems. Policymakers can propel the world's shift to cleaner and more environmentally friendly energy sources by encouraging innovation and cross-border cooperation.

ENVIRONMENTAL IMPACT

Combining RE and EVs offers a chance to slow environmental damage and advance sustainability. By aligning EV charging with RE generation, it is possible to drastically reduce GHG emissions, air pollution, and the overall carbon footprint of the transportation sector. This section explores the environmental benefits of this integration and addresses the potential environmental challenges associated with large-scale deployment.

Reduction of Greenhouse Gas Emissions

One of the most significant environmental impacts of integrating RE with EV charging is the reduction of GHG emissions. The combustion of fossil fuels in conventional ICE cars results in significant CO₂ emissions. By contrast, EVs produce no direct tailpipe emissions, making them cleaner. However, the environmental benefits of EVs are greatly enhanced when the electricity used for charging is derived from renewable sources, such as solar, wind, or hydroelectric power.

By powering EVs with RE, emissions associated with the electricity grid can be minimized, moving toward a net-zero transportation system. In regions where coal or natural gas dominate electricity generation, the shift to renewable-energy-powered EV charging has the potential to dramatically reduce the carbon footprint of EVs, accelerating the transition to a low-carbon economy.

For nations that have ratified international climate agreements, such as the Paris Agreement, which establishes aggressive goals for cutting global emissions to keep global warming far below 2°C, this decrease in GHG emissions is especially important. The transportation sector is one of the largest contributors to GHG emissions, and a shift to renewable-powered EV charging is essential for meeting these climate goals.

Air Quality Improvements

In addition to reducing GHG emissions, renewable energy-powered EVs can significantly improve air quality, especially in urban areas, where transportation is a major source of pollution. Conventional automobiles release pollutants, such as particulate matter (PM), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), which lead to respiratory problems, smog production, and other public health hazards.

As EVs replace ICE vehicles and the share of RE in the grid increases, cities will experience fewer emissions of these harmful pollutants. This leads to healthier living environments, reduced incidence of

respiratory diseases, and improved overall public health outcomes. Thus, the integration of RE with EV charging can play a pivotal role in enhancing the air quality and reducing pollution-related health costs.

In cities with high EV adoption, such as Oslo, Norway, and Shenzhen, China, air quality improvements have already been observed as a result of the shift to cleaner transportation options. These examples serve as models of how other cities can benefit from widespread EV adoption and RE integration.

Mitigating the Environmental Impact of EV Battery Production

Although EVs offer significant environmental benefits during their operation, the production of EV batteries remain a concern. Large quantities of raw minerals, such as lithium, cobalt, and nickel, are required to manufacture LIBs, which are frequently found in EVs. The mining and processing of these materials can harm the environment by destroying habitats, polluting water supplies, and using a large amount of energy.

However, RE sources can help mitigate these impacts. The lifecycle emissions of EVs can be further reduced by powering battery manufacturing plants with RE. Additionally, advancements in battery recycling and second-life applications of EV batteries are expected to minimize the environmental impact associated with battery disposal, creating a more sustainable battery ecosystem.

Furthermore, new developments in battery technology are imminent, including solid-state batteries and substitute chemistry that require fewer rare materials. These advancements will help decrease the environmental burden of battery production and make EVs more environmentally friendly.

Land Use and Resource Considerations for RE

Although RE sources such as solar and wind energy are far cleaner than fossil fuels, they still require significant amounts of land and natural resources for their development. For example, solar farms may require large areas of land, potentially disrupting ecosystems or competing for agricultural uses. Although they produce clean electricity, wind turbines can have adverse effects on nearby wildlife, especially in bat and bird communities.

To minimize these impacts, careful planning is necessary to optimize land use for RE projects. Solar panels can often be mounted on parking lots, rooftops, and other existing spaces, thus negating the need for new land. Additionally, advancements in floating solar farms and offshore wind farms are helping mitigate land use concerns by moving RE infrastructure away from sensitive terrestrial ecosystems.

The integration of RE with EV charging offers a multitude of environmental benefits, such as reducing GHG emissions and improving air quality to minimize the environmental impact of EV battery production. To guarantee that the shift to clean energy is genuinely sustainable, considerable consideration must be given to the resource and land use consequences of RE production. By addressing these challenges and continuing to innovate, renewable energy-powered EV charging can play a central role in achieving a cleaner and healthier planet.

ECONOMIC CONSIDERATIONS.

Determining the long-term feasibility and success of this shift depends heavily on the economics of combining RE with EV charging. While the environmental benefits of this integration are clear, the economic considerations involve analyzing the costs, potential savings, market opportunities, and economic incentives that drive the adoption of renewable-powered EV infrastructure. This section discusses the key economic factors, including capital investment, operational costs, and financial benefits of smart charging and V2G systems.

Initial Capital Investment

The initial capital investment required to develop and deploy a renewable energy-powered EV charging infrastructure is substantial. Widespread adoption may be hampered by the expense of

installing energy storage devices, sophisticated smart grid technology, and RE systems, such as wind turbines or solar panels, especially in areas with limited financing. For businesses, municipalities, or governments aiming to establish solar- or wind-powered EV charging stations, the upfront costs may include the following:

- The acquisition and setup of systems for producing RE.
- Purchasing battery storage will help control the intermittent nature of RE.
- Smart grid technology deployment to facilitate effective energy management.
- Construction of charging stations and the necessary electrical infrastructure.

However, the declining costs of RE technologies, particularly solar photovoltaics, and battery storage, make such investments more feasible. As prices continue to fall, the economic case of renewable-powered EV charging will become even stronger.

Long-Term Operational Savings

Long-term operational reductions can balance the potentially significant initial expenditures of EV charging stations fueled by RE. RE sources, such as solar and wind, have minimal ongoing fuel costs because they rely on naturally occurring energy sources rather than fossil fuels. Once the RE infrastructure is in place, the cost of electricity generation is close to zero, resulting in significant long-term savings for charging station operators and EV owners.

Moreover, energy storage systems that capture excess RE during periods of low demand can further reduce the operational costs. By storing and using this energy during peak demand periods, charging stations can avoid high electricity rates and provide cost-effective charging options to consumers. This reduces the reliance on the grid during expensive peak periods and improves the overall economic efficiency of the charging station.

Additionally, managed charging systems can help reduce costs by aligning EV charging with periods of lower energy prices or higher RE availability, thereby minimizing the economic burden on both consumers and grid operators.

Revenue Generation of V2G Systems

One of the most promising economic benefits of integrating RE with EV charging is the potential for revenue generation through vehicle-to-grid (V2G) systems. When consumption is high or RE generation is low, V2G allows EVs to release the stored energy back into the grid. This not only supports grid stability but also allows EV owners to sell electricity to the grid at premium rates during peak periods.

In V2G-enabled regions, EV owners can take advantage of dynamic pricing models by providing energy to the grid when electricity prices are the highest, thus earning revenue while also contributing to grid resilience. Grid operators benefit from access to distributed energy storage assets, reducing the need for expensive peaker plants or additional infrastructure to manage peak loads.

For businesses and municipalities that operate EV fleets, V2G can create a substantial new revenue stream. By intelligently managing fleet charging schedules and discharging energy during peak hours, fleet operators can significantly reduce their overall energy costs while earning income from grid services.

Economic Incentives and Government Policies

Government incentives and policy frameworks play a pivotal role in promoting the economic feasibility of renewable energy-powered EV charging. In many countries, subsidies, tax credits, and rebates are available to support the deployment of RE systems and EV infrastructure. These financial incentives help to reduce the capital costs associated with installing solar panels, wind turbines, and

energy storage systems, making renewable-powered charging stations more accessible to a broader range of stakeholders.

In addition, carbon pricing mechanisms and RE mandates can encourage the adoption of cleaner energy for EV charging by making it economically advantageous to shift away from fossil fuels. Policies that prioritize grid decarbonization and support RE development will create a more favorable economic environment for the integration of RE with EV charging.

For instance, feed-in tariffs or net metering programs can allow charging station operators to sell excess RE back to the grid, thereby further enhancing the financial viability of these systems. Governments that adopt policies encouraging the deployment of smart grids, V2G technologies, and decentralized RE will help accelerate the transition to cleaner, more economically sustainable energy systems.

CONCLUSION

The integration of EV charging with RE represents a critical step toward achieving a sustainable and low-carbon transportation ecosystem. In this study, we explored the technological, environmental, and economic aspects of combining EV infrastructure with RE sources, such as solar, wind, and hydro. As the world shifts away from fossil fuels to combat climate change, the convergence of clean transportation and RE has become an essential pathway for reducing GHG emissions, improving air quality, and promoting global sustainability goals.

Advancements in smart charging technologies, including unidirectional (V1G) and bidirectional (V2G) systems, offer exciting possibilities for optimizing the use of RE in EV charging. Through intelligent energy management, EVs can be charged during periods of high renewable generation and can even supply energy back to the grid during peak demand, thus enhancing grid flexibility and reducing reliance on fossil-fuel power plants. Coupled with energy storage solutions and power conversion technologies, the development of smart grids will be crucial for managing the fluctuating nature of RE and ensuring that clean electricity is always available for EVs.

From an environmental perspective, the shift to renewable-energy-powered EVs offers a dramatic reduction in GHG emissions and air pollutants, making urban environments healthier and aligning transportation with global climate targets.

However, challenges remain in mitigating the environmental impact of EV battery production and optimizing land use for the RE infrastructure. Through innovations in battery technology, recycling, and sustainable RE practices, these issues can be addressed to ensure a green future.

Economically, the integration of RE with EV charging presents both opportunities and challenges. Although upfront infrastructure costs can be high, long-term operational savings from low-cost RE, the potential for revenue generation from V2G systems, and government incentives make this transition financially viable. Governments must play a proactive role by implementing supportive policies such as subsidies, tax incentives, and carbon pricing mechanisms to encourage widespread adoption and investment in renewable-powered EV infrastructure.

Looking ahead, there is room for innovation in the integration of EVs and REs. Emerging technologies, such as wireless charging, dynamic energy management, and V2X systems, will shape how vehicles interact with the grid and contribute to a broader energy ecosystem. To fully realize the promise of this integration, energy storage technologies, smart grids, and sustainable energy policies must continue to advance.

In conclusion, the integration of EV charging with RE offers a transformative opportunity to decarbonize the transportation sector while supporting the global shift to clean, RE. By addressing the technical, environmental, and economic challenges outlined in this paper, stakeholders can create a resilient, efficient, and sustainable future for both the transportation and energy industries. Continued research, innovation, and collaboration across governments, industries, and communities are essential for accelerating this transition and ensuring a sustainable future for future generations.

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