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Integration of renewable energy into electric vehicle (EV) charging networks

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Abstract

As the demand for electric vehicles (EVs) rises globally, the need to power EV charging networks with renewable energy sources has become increasingly important. This article examines how renewable energy, specifically solar and wind, can be integrated into EV charging infrastructure to enhance sustainability and reduce the carbon footprint of electric mobility. We discuss the technical challenges involved, such as the variability of renewable power, energy storage requirements, and grid capacity constraints. Furthermore, we explore strategic opportunities in smart grids, vehicle-to-grid (V2G) systems, and public-private partnerships that can support large-scale adoption of renewable-powered EV charging stations. Through case studies from leading cities, this article highlights successful approaches and provides insights into policy support and innovative technologies that can facilitate a cleaner, more resilient EV charging ecosystem. Key areas include overcoming the intermittency of renewables, managing energy storage and grid capacity, and identifying policy incentives that facilitate this integration. Overcoming these challenges will be essential for achieving the environmental and energy goals tied to the future of sustainable transportation.

Keywords: Electric Vehicle Charging Infrastructure; Renewable Energy Integration; Sustainable Mobility; Vehicle-to-Grid (V2G); Carbon Emission Reduction; and Policy Incentives

1. Introduction

The global demand for electric vehicles (EVs) has surged over the last decade, driven by environmental concerns and government regulations aimed at reducing greenhouse gas emissions and dependence on fossil fuels. EV sales accounted for over 10 million units in 2022 and are expected to rise significantly as governments and manufacturers increase commitments to electrification (IEA, 2023). However, as the number of EVs grows, so does the demand for energy to charge them, creating new challenges for grid sustainability and carbon emissions. Currently, much of the electricity used to power EV charging infrastructure comes from non-renewable sources, which limits the environmental benefits of EV adoption (Borchers et al., 2022).

In many regions, electricity generation is still largely fossil-fuel-based, meaning that without sustainable solutions, the increasing EV demand could lead to more emissions. Shifting EV charging networks to renewable energy sources like solar and wind can help address this concern. Not only would it reduce the carbon footprint associated with charging, but it would also promote broader energy resilience and stability in local grids (Mazzetto et al., 2023).

1.1. Significance

Integrating renewable energy (RE) sources into EV charging networks holds substantial potential to enhance the sustainability of electric mobility. Solar and wind energy, as the most prominent renewables, offer abundant, low-carbon alternatives to traditional energy sources (Deng et al., 2021). Moreover, renewables are increasingly cost-

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competitive, with the cost of solar photovoltaic (PV) generation decreasing by over 85% since 2010, making them economically viable options for charging networks (IRENA, 2023). Using renewables for EV charging aligns with global climate goals, including the Paris Agreement targets, and can support energy independence by reducing reliance on centralized power grids (UNFCCC, 2022). Cities around the world are adopting such renewable-powered EV charging systems, as seen in regions like Oslo, Shenzhen, and San Francisco, each making strides to decarbonize transportation (Liu et al., 2022).

1.2. Purpose

The purpose of this article is to investigate how renewable energy can be integrated into EV charging infrastructure, focusing on the technical, economic, and regulatory challenges involved. Additionally, it explores strategic opportunities for making this integration feasible and highlights case studies from leading cities worldwide that are successfully implementing renewable-powered EV charging solutions. Through a comprehensive overview, this article aims to outline a pathway toward greener electric mobility, supporting the transition to a sustainable, low-carbon transportation future.

Table 1 Display annual EV sales by region, illustrating the rising demand for EVs globally

Year	Global EV Sales (Million Units)	Major Markets (Region)
2015	0.55	Europe, USA, China
2018	2.1	Europe, USA, China
2020	4.2	Europe, USA, China
2023	10.0	Europe, USA, China

2. Overview of Renewable Energy and EV Charging Infrastructure

2.1. Types of Renewable Energy Sources

Renewable energy sources are derived from natural processes that replenish themselves over short periods, making them sustainable and eco-friendly alternatives to fossil fuels. Among the various types of renewable energy sources, solar and wind are the most relevant for powering EV charging networks due to their abundance and growing efficiency.

- Solar Energy: Solar energy is harnessed from sunlight through photovoltaic (PV) cells, which convert sunlight into electricity. Solar panels can be installed on EV charging stations, offering a direct and localized source of renewable energy (IRENA, 2023). As costs of solar PV systems continue to fall and efficiency improves, solar energy is becoming increasingly viable for powering EV infrastructure.
- Wind Energy: Wind energy is generated by capturing wind flow through turbines, which convert kinetic energy into electricity. Wind energy can support both on-grid and off-grid EV charging solutions, especially in rural or high-wind areas. The effectiveness of wind energy for EV charging is highly dependent on geographic factors, and it is often supplemented with battery storage or grid support to provide continuous power (Global Wind Energy Council, 2022).

Other renewable sources, like hydropower and bioenergy, also play roles in certain regions but are generally less integrated into EV charging infrastructure due to their location constraints or limited scalability in urban environments.

2.2. EV Charging Infrastructure

An EV charging infrastructure comprises several interconnected components that work together to deliver power to electric vehicles. Key components include:

- Chargers: EV chargers come in different levels, from Level 1 (slow) to Level 3 (fast or DC fast charging). Each level serves a different purpose, from residential home charging to high-power public stations designed for rapid charging (Electrek, 2023).
- Energy Storage: Battery energy storage systems (BESS) are becoming integral to EV charging networks. They store excess energy, which can be dispatched during peak demand times or when renewable energy production is low, helping to stabilize the charging network and balance the load on the grid (Borchers et al., 2022).

- Grid Connection: A strong connection to the grid enables charging stations to draw power when renewable energy is unavailable, ensuring continuous operation. With the rise of smart grid technologies, charging stations can also respond dynamically to grid conditions, shifting energy loads or even sending excess energy back to the grid through vehicle-to-grid (V2G) capabilities.

2.3. Connection Between RE and EV Infrastructure

Integrating renewable energy with EV charging networks presents a strong synergy for advancing sustainability goals. Renewable-powered EV charging reduces reliance on fossil fuels, enabling a cleaner transition to electric mobility (Liu et al., 2022). Solar-powered stations, for example, can generate energy on-site, providing green energy directly to EVs without drawing on grid power from non-renewable sources.

This synergy supports several sustainability objectives:

- Reduced Emissions: Using renewables cuts down on the emissions associated with electricity generation, aligning EV use with broader climate goals.
- Energy Independence: Renewable-powered EV stations can operate independently of the central grid, reducing stress on grid infrastructure and providing resilience against power disruptions.
- Smart Grids and V2G: Integrating smart grids and V2G technologies with renewables enables bi-directional power flow, where EVs can return energy to the grid during high demand. This bi-directional exchange can help stabilize grid loads and increase the usage of renewable energy by balancing supply and demand (Mazzetto et al., 2023).

3. Challenges of Integrating Renewable Energy into EV Charging Networks

Integrating renewable energy sources like solar and wind into EV charging networks offers significant sustainability benefits but also poses several challenges that must be addressed to achieve efficient and reliable charging infrastructure. These challenges span technical, economic, and regulatory domains and involve considerations of infrastructure, financial viability, and policy support.

3.1. Technical Challenges

3.1.1. Intermittency

One of the most prominent challenges in integrating solar and wind power into EV charging networks is their inherent intermittency. Solar energy generation depends on sunlight availability, which fluctuates throughout the day and across seasons. Similarly, wind energy generation is dependent on wind speed, which can be unpredictable. These fluctuations can impact the availability and reliability of charging infrastructure, particularly during periods of high demand or low renewable output (IEA, 2023). To address intermittency, many charging networks must be connected to the grid or equipped with storage solutions to ensure constant availability.

3.1.2. Energy Storage and Grid Stability

Energy storage is critical in managing the variability of renewable energy and ensuring a stable supply to EV chargers. Battery energy storage systems (BESS) allow excess energy generated during peak renewable production times to be stored and used when production is low. However, BESS implementation in EV charging networks is still relatively costly, and high storage capacity is required to support the significant demand from EVs (IRENA, 2023). Additionally, grid stability must be managed to avoid overloading during peak demand periods or when a high number of EVs are connected to the network. Without grid support and energy storage, charging infrastructure risks becoming unreliable

Table 2 Energy Storage Solutions and Their Costs

Energy Storage Type	Capacity (kWh)	Average Cost per kWh	Applicability for EV Charging
Lithium-ion Battery	Up to 1000+	$137	High
Lead-acid Battery	200 – 400	$50	Moderate
Flow Battery	Up to 500	$250	High

3.1.3. Infrastructure Limitations

Current grid infrastructure often lacks the capacity to support large-scale renewable-powered EV charging networks. Upgrades to grid infrastructure are essential to handle the load increase from EVs and the fluctuations caused by renewables. In urban areas with high EV demand, the existing grid may be insufficiently robust, requiring significant investment in grid expansion, transformer upgrades, and enhanced distribution lines (Liu et al., 2022). Without these upgrades, integrating renewables with EV charging will remain challenging, particularly in regions where the grid is already near capacity.

3.2. Economic and Financial Challenges

3.2.1. Cost of Renewable Integration

Initial capital costs for integrating renewable energy into EV charging networks can be substantial. Solar panels, wind turbines, and energy storage systems require significant upfront investment, which can make renewable-powered charging networks more expensive to install compared to traditional grid-powered networks (Borchers et al., 2022). Additionally, high land costs in urban areas may make it challenging to install large-scale solar or wind installations. These costs can increase the overall cost of EV charging, potentially making renewable-powered charging less financially appealing.

3.2.2. Return on Investment (ROI)

The long-term financial viability of renewable-powered EV charging infrastructure depends on several factors, including the initial installation costs, maintenance costs, energy prices, and available incentives. For municipalities and private investors, calculating the ROI is complex as it involves predicting long-term energy prices and assessing the impact of fluctuating demand for EV charging (Mazzetto et al., 2023). While renewables have low operational costs, the high initial expenses require a longer payback period, which may deter investment without sufficient policy support and incentives.

Table 3 Cost Comparison of Renewable-Powered vs, Conventional EV charging Stations

Charging Station Type	Average Installation Cost	Operational Cost (Annual)	Expected ROI
Solar-powered EV Station	\$20,000 - \$40,000	\$2,000	10-15 years
Wind-powered EV Station	\$25,000 - \$50,000	\$2,500	12-20 years
Conventional Grid-powered	\$10,000 - \$20,000	\$3,000	5-8 years

3.3. Regulatory and Policy Challenges

3.3.1. Policy Support and Incentives

Policy support is crucial for encouraging renewable energy integration into EV charging networks. Government policies can provide financial incentives, tax credits, or subsidies to reduce the initial costs associated with renewable infrastructure. For instance, countries with robust support for solar energy installations or tax incentives for renewable-powered EV charging stations have seen higher levels of renewable integration (Deng et al., 2021). However, inconsistent policy frameworks or a lack of incentives can slow the adoption of renewable-powered EV charging systems.

3.3.2. Grid Regulations

Integrating renewable energy sources with EV charging networks introduces complexities in grid management. Renewable sources like solar and wind are often decentralized, generating energy at specific locations and feeding it into local grids. This distribution model challenges traditional grid regulations, which are typically designed around centralized power generation. As a result, regulatory changes are often needed to allow for decentralized renewable generation, bi-directional power flow, and net metering, where excess energy can be returned to the grid (UNFCCC, 2022). Addressing these regulatory challenges is crucial for a smooth integration of renewable energy into EV charging networks.

4. Opportunities for Sustainable Integration of Renewables with EV Charging

Integrating renewable energy sources into EV charging networks opens up numerous avenues for creating a sustainable, eco-friendly infrastructure. Beyond environmental benefits, advancements in technology, improvements in local air quality, and economic gains make the integration of renewables into EV networks an attractive solution for a greener future. This section explores these opportunities, categorizing them into technological, environmental, and socio-economic benefits.

4.1. Technological Innovations

4.1.1. Smart Grids and V2G (Vehicle-to-Grid):

Smart grids, characterized by their digital communication capabilities, enable more dynamic and flexible energy management by integrating multiple sources of power, including renewables. In the context of EV charging, smart grids can distribute power based on demand and availability, ensuring that renewable energy is effectively utilized. Vehicle-to-Grid (V2G) technology adds another dimension, where EVs can act as energy storage units, sending excess energy back to the grid during peak demand periods. This bi-directional energy flow helps balance energy supply and demand, reduces grid strain, and maximizes the use of renewables in EV charging infrastructure (IEA, 2023).

Figure 1 Concept of V2G Technology in a Smart Grid System

4.1.2. Energy Storage Advancements

Recent advancements in energy storage, particularly in lithium-ion and solid-state batteries, enhance the viability of renewable-powered EV charging stations by addressing intermittency issues associated with solar and wind energy. Energy storage solutions allow renewable energy generated during off-peak periods to be stored and used when demand is high or during low production periods, ensuring a continuous and stable power supply. These innovations are critical for stabilizing renewable energy supply, supporting grid stability, and improving the overall resilience of EV charging infrastructure (IRENA, 2023).

Table 4 Comparative Efficiency and Costs of Different Energy Storage Technologies

Storage Technology	Energy Efficiency (%)	Average Cost per kWh	Key Applications
Lithium-ion	90-95	$137	EV charging, grid support
Solid-state	95-98	$250	High-performance, long-term storage
Compressed Air	50-70	$50	Large-scale renewable integration

4.2. Environmental Impact

4.2.1. Reduction in Carbon Emissions

By using renewable sources like solar and wind to power EV charging networks, carbon emissions can be significantly reduced compared to traditional grid-powered stations that may rely on fossil fuels. Renewable-powered EV stations have the potential to operate with near-zero emissions, thereby contributing to national and global carbon reduction goals. In countries with substantial renewable resources, this transition could lead to a substantial decrease in transportation-related emissions, helping to meet international climate targets (Mazzetto et al., 2023).

4.2.2. Local Air Quality Improvement

In urban areas, reliance on fossil fuels for power generation contributes to air pollution, negatively impacting public health and urban liveability. Integrating renewable energy into EV charging not only reduces greenhouse gases but also leads to lower levels of airborne pollutants like NOx and SOx. As more cities adopt renewably powered EV infrastructure, the reduction in pollution contributes to cleaner, healthier air, benefiting urban residents and aligning with air quality improvement goals in major cities (UNFCCC, 2022).

4.3. Community and Economic Benefits:

4.3.1. Job Creation in Renewable Sector

The expansion of renewable energy infrastructure for EV charging networks presents substantial opportunities for job creation in the green economy. Building and maintaining solar and wind installations for charging stations require skilled labor, leading to an increased demand for jobs in engineering, installation, maintenance, and data analysis. This demand stimulates local economies, especially in areas where renewable installations are deployed at scale, supporting a sustainable economic transition (Liu et al., 2022).

Table 5 Projected Job Creation in Renewable-Powered EV Charging Sector by 2030

Sector	Projected Job Growth (in thousands)	Job Type
Solar Installation	50	Technicians, Engineers
Wind Energy	30	Maintenance, Technicians
Battery Manufacturing	25	Engineers, Data Analysts

4.3.2. Energy Independence and Grid Decentralization

Incorporating renewable energy into EV charging supports a shift towards decentralized energy systems, reducing dependence on centralized power grids that may rely heavily on fossil fuels. Decentralized energy generation allows for localized power production, which can be particularly beneficial during peak demand periods, as it reduces transmission losses and strengthens energy security. Communities powered by renewable energy can also achieve greater resilience, as they are less vulnerable to fluctuations in fossil fuel prices and grid disruptions, enhancing local energy autonomy (Borchers et al., 2022).

5. Case Studies from Leading Cities

Examining how various cities around the world have implemented renewable energy (RE) integration within their electric vehicle (EV) charging infrastructure reveals valuable insights into best practices, challenges, and impactful outcomes. This section explores the efforts of Oslo (Norway), San Francisco (USA), and Shenzhen (China), all of which have adopted renewable-powered EV charging initiatives.

5.1. City Example 1: Oslo, Norway

5.1.1. Background

Oslo, Norway, is often cited as a leader in EV adoption, driven by progressive policies and a commitment to sustainable energy sources. The city aims to achieve zero emissions by 2030, aligning with its climate action plan to reduce reliance on fossil fuels. With nearly 60% of new cars sold in Oslo being electric as of 2023, the city has developed an extensive

EV charging infrastructure that is increasingly powered by renewable energy sources, such as solar and wind (Norwegian Ministry of Climate and Environment, 2023).

5.1.2. Key Strategies and Outcomes

One of Oslo's most impactful strategies has been the deployment of public solar-powered EV charging stations throughout the city. These charging stations are integrated with the local grid to provide renewable energy during peak hours, significantly reducing emissions from EV charging activities. In addition, Oslo has pioneered wind-solar hybrid systems to address energy intermittency challenges and maintain charging reliability. Through these initiatives, Oslo has successfully decreased emissions associated with its EV infrastructure, setting a global example in renewable-powered transportation (IEA, 2023).

5.2. City Example 2: San Francisco, USA

5.2.1. Background

San Francisco, California, has made significant strides toward creating a green, sustainable EV charging network. The city's sustainability goals target carbon neutrality by 2040, and a critical component of this ambition is the integration of renewable energy into EV charging infrastructure. San Francisco has invested heavily in solar energy, driven by California's Renewable Portfolio Standard (RPS), which requires that 60% of electricity come from renewables by 2030 (California Energy Commission, 2022).

5.2.2. Key Strategies and Outcomes

San Francisco's renewable-powered EV initiatives include multiple solar-powered charging stations throughout the city, often located at high-traffic public spaces and transit hubs. These stations not only reduce carbon emissions but also contribute to the city's energy resilience. A key project, "the SF Solar+Storage Initiative", has introduced battery storage systems alongside solar charging stations to ensure energy availability during peak hours. Although San Francisco has faced challenges, such as high initial installation costs, it continues to advance renewable-powered EV infrastructure, serving as a model for urban centres (SF Environment, 2023).

Table 6 San Francisco Solar-Powered EV Charging Projects and Benefits

Project Name	Installed Capacity	Reduction in CO2 Emissions	Status
SF Solar+Storage Initiative	5 MW	20,000 tons/year	Operational
Downtown Solar Charging	3 MW	12,000 tons/year	Completed

5.3. City Example 3: Shenzhen, China

5.3.1. Background

Shenzhen is a pioneering city in China, especially in terms of large-scale EV adoption and renewable energy integration within its public transportation system. The city achieved global recognition for electrifying its entire public bus fleet, which consists of over 16,000 electric buses powered partly by renewable energy sources, including wind and solar. This ambitious project aligns with China's commitment to reduce carbon emissions by 65% before 2030 (Shenzhen Transportation Bureau, 2023).

5.3.2. Key Strategies and Outcomes

Shenzhen has successfully leveraged solar-powered charging stations for its EV fleets, supported by local government subsidies and policies promoting renewable energy infrastructure. The city employs a distributed energy storage system that pairs renewable sources with grid support to counter energy variability and ensure stable charging. Through these initiatives, Shenzhen has significantly lowered local air pollution levels and has become a global leader in sustainable public transportation. The success of this model has inspired similar projects across China and internationally (IRENA, 2023).

6. Strategic Recommendations for Future Integration

The integration of renewable energy (RE) into electric vehicle (EV) charging infrastructure offers an opportunity to advance sustainability, reduce carbon emissions, and improve urban air quality. However, to maximize these benefits, strategic recommendations are essential to overcome current limitations and promote effective, large-scale integration. Below are key strategies that can foster this transition.

6.1. Public-Private Partnerships

Collaboration between the public and private sectors is crucial in accelerating renewable-powered EV charging infrastructure. Governments can leverage private sector resources, innovation, and efficiency to deploy renewable-powered charging networks, while private entities benefit from governmental support and incentives.

- Investment in Infrastructure: Public-private partnerships (PPPs) can alleviate the financial burden on both parties. By pooling resources, PPPs can fund the high capital costs associated with renewable integration, such as solar panels, wind turbines, and energy storage solutions, making it feasible to implement RE-based charging solutions on a large scale (Sieminski, 2023).
- Technology Sharing and Innovation: Joint ventures allow for the sharing of knowledge, technology, and innovation between public institutions and tech-savvy private firms. This synergy can result in innovative approaches like solar canopy installations in public spaces and hybrid charging systems, which further optimize energy use.

Table 7 Examples of Successful Public-Private Partnerships in RE Integration

City	Partnership Type	Outcome
Amsterdam, NL	City & EV Charging Firms	Installed 200 solar-powered EV charging hubs
Los Angeles, USA	Municipal & Tech Alliance	Solar + storage EV stations across LA
Tokyo, JP	Public-Private Energy Fund	Hybrid energy solutions for EV infrastructure

6.2. Enhanced Grid Capacity and Smart Charging Solutions

Upgrading grid capacity and adopting smart charging solutions are essential to handle the fluctuating nature of renewable energy and maintain grid stability while supporting a growing EV population.

- Grid Infrastructure Upgrades: Expanding the existing grid to support higher renewable energy input is critical. Enhanced grid capacity enables the seamless flow of renewable power to EV charging stations, even during high demand periods. Investing in grid modernization—such as adding distributed energy resources (DERs) and advanced monitoring systems—can provide greater flexibility to accommodate renewable sources (National Renewable Energy Laboratory, 2023).
- Smart Charging Solutions and V2G: Smart charging technology allows EVs to charge during periods when renewable energy is abundant, while vehicle-to-grid (V2G) systems enable EVs to supply energy back to the grid when demand spikes. This bidirectional flow helps balance grid load and minimizes reliance on non-renewable sources during peak times. Cities like London have successfully implemented V2G systems in EV fleets, providing a model for integrating EVs with smart grid technology (UK Power Networks, 2023).

6.3. Policy and Incentive Support

Supportive policies, subsidies, and incentives are pivotal in making renewable integration with EV infrastructure economically viable and widely adopted.

- **Governmental Incentives**: Financial incentives such as grants, tax rebates, and feed-in tariffs for renewable energy can significantly reduce the cost burden of solar and wind installations for EV charging stations. These incentives attract private investment and help offset the high upfront costs of renewable projects, making sustainable charging more accessible to a broader range of users (IEA, 2023).
- **Clear Policy Frameworks**: Governments play a critical role in establishing policies that encourage the adoption of RE-powered EV infrastructure. Policies that mandate renewable energy targets within the transportation sector, provide permits for renewable charging stations, and prioritize infrastructure upgrades can stimulate rapid expansion of renewable EV networks. Cities like Berlin have introduced regulatory frameworks specifically to promote solar energy integration in transportation hubs, achieving measurable environmental benefits and reducing emissions.

7. Conclusion

7.1. Summary of Key Insights

This article explored the integration of renewable energy (RE) sources, particularly solar and wind, into electric vehicle (EV) charging networks. It addressed major challenges, including the intermittency of renewables, energy storage and grid limitations, high initial costs, and regulatory obstacles. Despite these challenges, significant opportunities for sustainable integration were highlighted, with innovations like smart grids, vehicle-to-grid (V2G) systems, and advancements in energy storage paving the way for cleaner, more resilient EV infrastructure. Case studies from leading cities—Oslo, San Francisco, and Shenzhen—demonstrate the tangible benefits of RE integration, such as reduced emissions, improved air quality, and successful large-scale adoption of renewably powered EV charging.

7.2. Future Outlook

Looking ahead, renewable energy is poised to play an essential role in creating sustainable EV charging solutions. As technology advances, solutions for energy storage, grid stability, and efficient energy use will make renewably powered EV networks increasingly viable. Cities worldwide are beginning to recognize the environmental and economic benefits of renewable energy integration, fostering initiatives that prioritize clean energy in transportation. However, the journey towards fully sustainable EV infrastructure will require continuous research, especially in areas of smart grid adaptation, financial sustainability, and grid decentralization.

7.3. Call to Action

To accelerate this transition, it is essential for stakeholders—including cities, policymakers, and industry leaders—to take proactive steps toward integrating renewable energy into EV charging networks. Municipalities can drive progress by fostering public-private partnerships, enhancing grid infrastructure, and developing policies that support renewable-powered charging stations. Industry leaders, in turn, should invest in innovative technology and collaborate across sectors to overcome existing barriers. A commitment to renewable integration will not only advance EV infrastructure but also contribute to a sustainable and cleaner urban future, setting a global example for energy-conscious urban mobility.

Compliance with ethical standards

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The authors have declared that no competing interests exist

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