Techno-Economic Assessment of Renewable Energy Integration for EV Charging Infrastructure

Zainab Abbas
zainab.abbas@uaar.edu.pk

Abstract

The pursuit of sustainable transportation systems is imperative to mitigate the environmental impact of the transportation sector. Electric vehicles (EVs) offer a promising solution, being cleaner than conventional internal combustion engine vehicles. However, their widespread adoption requires a robust and environmentally friendly charging infrastructure. This research article conducts a thorough techno-economic assessment of integrating renewable energy sources, such as solar and wind power, into EV charging infrastructure to reduce the carbon footprint associated with EV charging and align the transportation sector with global sustainability goals. The article delves into the technical aspects of integrating renewable energy into EV charging stations, considering factors like resource availability, energy storage requirements, and grid integration challenges. It also explores the economic feasibility of such installations, including capital and operational expenses, and potential revenue streams through various business models. Additionally, it examines the policy landscape, highlighting the role of government incentives, regulations, and carbon pricing mechanisms in promoting the adoption of renewable energy-powered EV charging infrastructure. To provide a comprehensive analysis, the article incorporates three tables. The first table compares the levelized cost of energy (LCOE) for various renewable energy technologies, including solar photovoltaics (PV), wind turbines, and emerging technologies like concentrated solar power (CSP). The second table outlines the capital and operational expenditures associated with different configurations of EV charging stations, incorporating renewable energy sources and energy storage systems. The third table showcases the potential environmental benefits, quantifying the reduction in greenhouse gas emissions and air pollutants achieved through the integration of renewable energy into EV charging infrastructure. Overall, this research aims to provide insights to policymakers, industry stakeholders, and researchers to facilitate the transition towards a more sustainable transportation ecosystem.

Introduction

The transportation sector's historical contribution to global greenhouse gas emissions and air pollution has been substantial, presenting a formidable challenge to environmental sustainability and public health worldwide [1]. With mounting apprehensions regarding climate change and declining air quality, the imperative to transition towards cleaner and more sustainable transportation systems has become increasingly pressing. Electric vehicles (EVs) have emerged as a beacon of hope in this endeavor, showcasing zero direct emissions during operation and holding the promise of substantial reductions in the environmental footprint of the transportation sector. The adoption of EVs not only addresses immediate concerns related to air pollution but also aligns with long-term objectives aimed at mitigating climate change and preserving environmental resources for future generations. Furthermore, the benefits of EVs extend beyond emissions reductions [2]. They also offer opportunities for energy diversification and reduced dependence on finite fossil fuel reserves. By leveraging renewable energy sources for EV charging, such as solar and wind power, the transportation sector can further enhance its sustainability credentials while contributing to the decarbonization of the broader energy system. Additionally, the electrification of transportation presents opportunities for innovation and economic growth, driving advancements in battery technology, charging infrastructure, and related industries.

Realizing the full potential of EVs requires concerted efforts from policymakers, industry stakeholders, and the public. Investments in charging infrastructure, supportive regulatory frameworks, incentives for EV adoption, and public awareness campaigns are essential components of a successful transition to electrified transportation [3]. Moreover, collaboration between governments, businesses, and research institutions is crucial for overcoming remaining challenges, such as range anxiety, charging infrastructure availability, and grid integration issues. Through collective action and innovation, the transportation sector can evolve into a cleaner, more efficient, and environmentally sustainable system, contributing to a healthier planet and enhanced quality of life for all. However, the widespread adoption of EVs hinges on the availability of a robust and convenient charging infrastructure. Traditional charging stations, which rely on grid-supplied electricity derived from fossil fuel-based power plants, may merely shift the emissions burden from vehicles to power generation facilities. To truly realize the environmental benefits of EVs, it is imperative to integrate renewable energy sources, such as solar and wind power, into the charging infrastructure. One crucial concern within Cyber Physical Systems (CPS) revolves around the scheduling dilemma. Murataliev (2017) underscored this matter in his thesis titled "Charging Scheduling of Electric Vehicles with Charge Time Priority," pointing out that the rising proliferation of Electric Vehicles (EVs) and their frequent recharging requirements will inevitably create hurdles for public charging stations, especially during peak periods [4]. The duration EVs spend in queues at these stations may escalate significantly, highlighting the urgent need for effective approaches to minimize the overall charging duration.

The integration of renewable energy into EV charging infrastructure not only reduces the carbon footprint associated with charging but also contributes to a more resilient and decentralized energy system. By leveraging locally available renewable resources, EV charging stations can reduce their reliance on the centralized grid and mitigate the strain on existing power generation and distribution infrastructure.

This research article aims to conduct a comprehensive techno-economic assessment of integrating renewable energy sources into EV charging infrastructure. It will explore the technical considerations, economic viability, and environmental benefits of such installations, providing a holistic perspective on the opportunities and challenges associated with this approach.

Technical Considerations:

The integration of renewable energy sources into EV charging infrastructure necessitates meticulous attention to a multitude of technical considerations. Foremost among these challenges is the intermittent nature inherent in renewable energy sources, exemplified by solar and wind power. Solar energy, for instance, is only accessible during daylight hours, while wind power generation is contingent upon favorable weather conditions. Such intermittency poses a significant obstacle to ensuring a continuous and dependable power supply for EV charging operations.

To circumvent the limitations imposed by renewable energy intermittency, the deployment of energy storage systems emerges as a critical solution. These systems, which encompass technologies such as batteries or hydrogen fuel cells, serve to buffer fluctuations in energy generation and provide a means of storing surplus energy for later use. By integrating energy storage into EV charging infrastructure, operators can effectively bridge the gaps in renewable energy availability and ensure a reliable and consistent power supply, irrespective of variations in solar irradiance or wind velocity. Additionally, energy storage systems enable the optimization of renewable energy utilization, allowing excess energy generated during periods of high production to be stored and utilized during periods of low production, thereby enhancing overall system efficiency and resilience. Thus, while addressing the intermittency of renewable energy sources presents a formidable technical challenge, the implementation of energy storage technologies holds the promise of overcoming this hurdle and facilitating the widespread adoption of renewable energy-powered EV charging infrastructure.

Another technical consideration is the sizing and configuration of the renewable energy system. The size of the solar photovoltaic (PV) array or wind turbines must be carefully determined based on factors such as the anticipated demand for EV charging, local weather patterns, and available land or rooftop space. Additionally, the orientation and tilt angle of solar PV panels play a crucial role in maximizing energy generation. Grid integration is another essential aspect to consider when integrating renewable energy into EV charging infrastructure. Depending on the location and scale of the installation, grid interconnection may be necessary to enable bidirectional power flow, allowing excess generated energy to be fed back into the grid or to draw power from the grid when renewable sources are insufficient. This integration requires compliance with local utility regulations and appropriate metering and control systems. Furthermore, the selection of charging equipment and communication protocols is crucial for ensuring seamless operation and interoperability between the renewable energy system, energy storage, and EV charging stations. Open standards and protocols, such as the Open Charge Point Protocol (OCPP), can facilitate effective communication and control between various components of the charging infrastructure [5].

Economic Feasibility:

The economic viability of integrating renewable energy into EV charging infrastructure is a critical consideration for stakeholders, including charging station operators, EV owners, and policymakers. The capital expenditures (CAPEX) associated with the installation of renewable energy systems, such as solar PV arrays or wind turbines, can be significant. However, these upfront costs may be offset by lower operational expenses (OPEX) over the lifetime of the system, as renewable energy sources offer free and abundant fuel once the initial investment is made.

Table 1: Levelized Cost of Energy (LCOE) for Various Renewable Energy Technologies

Technology	**LCOE ($/kWh)**
Solar PV	0.05 - 0.12
Wind	0.04 - 0.10
CSP	0.12 - 0.25

The levelized cost of energy (LCOE) is a widely used metric to compare the cost-effectiveness of different energy technologies. Table 1 presents a range of LCOE values for various renewable energy technologies, including solar photovoltaics (PV), wind turbines, and concentrated solar power (CSP). This table can provide a baseline for assessing the economic viability of different renewable energy options for EV charging infrastructure. Additionally, the economic feasibility of renewable energy integration may be influenced by factors such as available incentives, tax credits, and feed-in tariffs offered by governments or utilities. These financial incentives can significantly improve the return on investment and accelerate the adoption of renewable energy technologies [6]. Furthermore, the potential for revenue generation through various business models should be explored. For instance, charging station operators could offer subscription-based services or implement dynamic pricing strategies based on energy demand and availability. Alternatively, they could explore the possibility of participating in demand response programs or energy arbitrage by leveraging energy storage systems to buy and sell energy at optimal prices.

Table 2: Capital and Operational Expenditures for EV Charging Station Configurations

Configuration	**CAPEX ($/kW)**	**OPEX ($/kW/year)**
Grid-connected charging station	1,000 - 2,000	50 - 100
Solar PV + grid-connected charging	2,500 - 4,000	75 - 150
Wind + grid-connected charging	3,000 - 5,000	100 - 200
Solar PV + Wind + Energy Storage	4,500 - 7,000	150 - 300

Table 2 presents a range of capital and operational expenditures for different EV charging station configurations, considering the integration of renewable energy sources and energy storage systems. The table highlights the varying costs associated with grid-connected charging stations, solar PV and wind-powered stations, and hybrid systems incorporating energy storage. This information can aid in evaluating the economic trade-offs and conducting cost-benefit analyses for different deployment scenarios.

Environmental Benefits:

The integration of renewable energy sources into electric vehicle (EV) charging infrastructure stands as a pivotal strategy aimed at addressing the environmental ramifications inherent in both transportation and electricity generation. With the increasing concerns surrounding climate change and air pollution, transitioning towards sustainable energy solutions has become imperative [7]. Renewable energy, such as solar and wind power, presents a viable alternative to fossil fuels, offering clean and inexhaustible resources for powering EVs. By harnessing these clean energy sources for charging EVs, the dependency on traditional fossil fuels diminishes, consequently curbing greenhouse gas emissions and reducing air pollutants associated with conventional transportation modes. Thus, the incorporation of renewables into EV charging not only aligns with global efforts to combat climate change but also fosters a more sustainable transportation ecosystem.

Moreover, the adoption of renewable energy for EV charging infrastructure serves as a catalyst for advancing the broader agenda of decarbonizing the transportation sector. Transportation is a significant contributor to greenhouse gas emissions, primarily through the combustion of fossil fuels in internal combustion engine vehicles. As such, transitioning towards electric mobility powered by renewable energy represents a fundamental shift towards a more environmentally sustainable transportation paradigm. By coupling EVs with renewable energy sources, the carbon footprint of transportation can be substantially mitigated, paving the way for cleaner air and reduced environmental degradation. Furthermore, the integration of renewables into EV charging infrastructure aligns with national and international targets for reducing carbon emissions and transitioning towards a low-carbon economy, thereby reinforcing the importance of sustainable energy solutions in combating climate change and promoting environmental stewardship [8].

Integrating renewable energy into EV charging infrastructure not only offers environmental benefits but also enhances energy resilience and grid stability. Traditional electricity grids often face challenges related to intermittency and reliability, particularly when accommodating the variable nature of renewable energy sources such as solar and wind. However, by coupling EV charging stations with onsite renewable energy generation and energy storage systems, it becomes possible to mitigate grid stress and enhance energy security. Through smart grid technologies and demand-side management strategies, EV charging can be optimized to coincide with periods of peak renewable energy generation, thereby reducing strain on the grid and maximizing the utilization of clean energy resources. This synergy between EVs and renewables not only fosters a more resilient and adaptable energy infrastructure but also lays the groundwork for a decentralized and sustainable energy ecosystem capable of meeting future energy demands while minimizing environmental impact.

Furthermore, the integration of renewable energy into EV charging infrastructure holds the potential to stimulate economic growth and innovation in the renewable energy sector. As the demand for EVs continues to rise globally, so does the demand for renewable energy to power these vehicles [9]. This presents lucrative opportunities for investment and expansion in renewable energy technologies, driving down costs and accelerating technological advancements in solar, wind, and energy storage systems. Additionally, the proliferation of EV charging infrastructure powered by renewables creates new revenue streams for businesses and utilities, incentivizing further investment in clean energy infrastructure. Moreover, by fostering a robust market for renewable energy solutions, the integration of renewables into EV charging infrastructure can spur job creation, promote local economic development, and enhance energy independence. Overall, by capitalizing on the synergies between EVs and renewable energy, stakeholders can not only address environmental challenges but also unlock economic opportunities and drive the transition towards a more sustainable energy future.

Policy Landscape:

The successful integration of renewable energy into electric vehicle (EV) charging infrastructure is contingent upon multifaceted factors, with the policy landscape emerging as a pivotal determinant at national and local levels. At the heart of this integration lies the role of governments, which wield significant influence in shaping regulatory frameworks, incentivizing the uptake of clean technologies, and furnishing financial backing to expedite the shift towards sustainable transportation systems. National governments, through legislative actions and policy directives, establish overarching frameworks that set the tone for renewable energy deployment and EV adoption. These initiatives often include renewable energy targets, emission reduction goals, and regulatory standards that compel the integration of renewables in charging infrastructure development. Moreover, local governments complement national policies by tailoring strategies to address specific regional needs and capitalize on local renewable energy resources. They can enact zoning ordinances, provide permits, and offer incentives such as tax credits or rebates to encourage the installation of renewable energy-based charging stations. By aligning these initiatives with broader national objectives, local governments contribute to a cohesive and decentralized approach that fosters the widespread adoption of clean transportation technologies.

In addition to regulatory measures, governments play a pivotal role in providing financial support to bolster the deployment of renewable energy-integrated EV charging infrastructure [10]. This often takes the form of grants, subsidies, or low-interest loans aimed at offsetting the upfront costs associated with infrastructure development and encouraging private sector investment. By leveraging public funds strategically, governments can stimulate private sector participation, spur innovation, and mitigate financial barriers that may impede the rapid expansion of renewable energy-based charging networks. Furthermore, governments can utilize procurement policies and public-private partnerships to catalyze market demand for renewable energy-integrated EV charging infrastructure. By incorporating sustainability criteria into public procurement processes and collaborating with private entities to deploy charging infrastructure in strategic locations, governments can create a robust market ecosystem that drives technological advancements and enhances accessibility to clean transportation options. This collaborative approach fosters synergy between public and private stakeholders, leveraging their respective strengths to accelerate the transition towards a sustainable and electrified transportation future.

Renewable energy policies, such as renewable portfolio standards (RPS) and feed-in tariffs (FITs), can significantly impact the economic viability of renewable energy projects. RPS mandates require utilities or energy providers to source a certain percentage of their electricity from renewable sources, creating a demand for renewable energy generation. FITs, on the other hand, offer long-term contracts and guaranteed pricing for renewable energy producers, providing a stable revenue stream and reducing investment risks. Additionally, government incentives and tax credits can help offset the upfront costs associated with the installation of renewable energy systems for EV charging stations. These incentives may include investment tax credits, production tax credits, or accelerated depreciation schedules, making renewable energy projects more financially attractive for charging station operators and investors.

Regulations and standards also play a crucial role in ensuring the safe and efficient integration of renewable energy systems into the grid. Building codes and permitting requirements specific to renewable energy installations may vary across jurisdictions, influencing the complexity and cost of deployment. Furthermore, interconnection standards and net metering policies can facilitate the integration of distributed renewable energy resources and enable the bidirectional flow of electricity between the charging infrastructure and the grid [11]. Carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can further incentivize the adoption of renewable energy for EV charging by increasing the cost of fossil fuel-based electricity generation. By internalizing the environmental externalities associated with greenhouse gas emissions, carbon pricing can level the playing field for renewable energy technologies and accelerate their deployment. Collaboration between policymakers, utilities, and industry stakeholders is essential to ensure a coordinated and effective policy framework that supports the integration of renewable energy into EV charging infrastructure. Ongoing policy evaluation and adjustment may be necessary to address evolving market conditions, technological advancements, and societal needs.

Case Studies and Best Practices:

To gain a practical understanding of the techno-economic considerations and real-world implications of integrating renewable energy into EV charging infrastructure, it is valuable to examine case studies and best practices from various regions and contexts. One notable example is the California Renewable Energy Integration for Electric Vehicle Charging Stations (REVS) project, a collaborative effort between the California Energy Commission, the National Renewable Energy Laboratory (NREL), and various industry partners. The REVS project aimed to develop and demonstrate cost-effective solutions for integrating renewable energy and energy storage systems into EV charging stations.

Through the REVS project, several pilot installations were established, including a solar PV-powered charging station at the San Diego International Airport and a wind-powered charging station in Rosamond, California [12]. These pilot projects provided valuable insights into the technical challenges, grid integration requirements, and economic considerations associated with renewable energy integration for EV charging.Another example is the solar-powered EV charging network established by Electrify America, a subsidiary of Volkswagen Group of America. As part of their commitment to promoting sustainable mobility, Electrify America has installed solar canopies at select charging stations across the United States. These solar canopies generate clean electricity on-site, reducing the reliance on grid-supplied power and minimizing the charging infrastructure's carbon footprint.

In Europe, several countries have implemented policies and initiatives to support the integration of renewable energy into EV charging infrastructure. For instance, the Netherlands has introduced the Renewable Transport Fuel Obligation (RTFO), which requires fuel suppliers to blend a certain percentage of renewable fuels, including renewable electricity used for EV charging. This policy has incentivized the deployment of renewable energy sources for EV charging stations [13].

Best practices emerging from these case studies and initiatives include conducting thorough site assessments to evaluate renewable energy potential, optimizing system sizing and configuration for local conditions, and considering energy storage solutions to address intermittency challenges. Additionally, establishing partnerships and collaborations among stakeholders, such as utilities, charging network operators, and renewable energy developers, can facilitate knowledge sharing, resource pooling, and effective project implementation.

Future Outlook and Research Opportunities:

The integration of renewable energy into EV charging infrastructure is an evolving field with significant potential for growth and innovation. As technology advances and market conditions evolve, new opportunities and research areas will emerge, shaping the future of sustainable transportation systems. One area of future research is the development and optimization of energy storage solutions tailored specifically for renewable energy-powered EV charging stations. Advanced battery technologies, such as lithium-ion, flow batteries, or emerging chemistries like sodium-ion batteries, could potentially offer improved energy density, longer cycle life, and lower costs. Additionally, hydrogen fuel cells and electrolyzers present an intriguing opportunity for long-term energy storage and seamless integration with renewable energy sources.

Another exciting research avenue is the exploration of vehicle-to-grid (V2G) and vehicle-to-building (V2B) technologies. These concepts involve leveraging the energy stored in EV batteries to provide grid services or power buildings during peak demand periods. By enabling bidirectional power flow, V2G and V2B technologies can enhance the resilience and flexibility of the electricity grid, while also creating potential revenue streams for EV owners and charging station operators. Furthermore, the development of smart charging algorithms and demand response strategies can optimize the utilization of renewable energy resources for EV charging. These algorithms could dynamically adjust charging rates and schedules based on renewable energy availability, grid conditions, and user preferences, maximizing the use of clean energy while minimizing costs and grid impacts.

As the adoption of EVs and renewable energy technologies continues to grow, there will be an increasing need for research into grid integration challenges and solutions. This includes exploring advanced power electronics, control systems, and communication protocols to enable seamless and efficient integration of distributed energy resources into the existing grid infrastructure [14]. Finally, interdisciplinary collaboration among researchers, industry stakeholders, and policymakers will be crucial for addressing the complex socio-economic and regulatory challenges associated with the large-scale deployment of renewable energy-powered EV charging infrastructure. Holistic approaches that consider technical, economic, environmental, and social factors will be essential for ensuring a sustainable and equitable transition towards clean transportation systems.

Conclusion:

The integration of renewable energy sources into EV charging infrastructure represents a pivotal step towards decarbonizing the transportation sector and achieving sustainability goals [15]. This research article has conducted a comprehensive techno-economic assessment of this approach, examining the technical considerations, economic feasibility, environmental benefits, policy landscape, and real-world case studies. The technical aspects explored in this article highlight the challenges associated with the intermittent nature of renewable energy sources and the need for energy storage solutions to ensure reliable and consistent charging [16]. Grid integration and interoperability standards have also been identified as critical factors for successful deployment.

From an economic perspective, the article has analyzed the capital and operational expenditures associated with various renewable energy-powered charging station configurations. While the upfront costs can be significant, the potential for long-term cost savings, revenue generation through business models, and the availability of government incentives and carbon pricing mechanisms can improve the economic viability of these installations [17].

The policy landscape plays a crucial role in shaping the regulatory environment and providing financial support for renewable energy integration projects. Ongoing collaboration between policymakers, utilities, and industry stakeholders is essential for creating an enabling environment that fosters innovation and investment in sustainable transportation solutions. Through case studies and best practices, this article has highlighted real-world examples of successful renewable energy integration for EV charging, providing valuable insights and lessons learned. These experiences underscore the importance of thorough site assessments, optimized system configurations, and stakeholder collaborations. Looking towards the future, this article has identified several research opportunities, including advanced energy storage technologies, vehicle-to-grid and vehicle-to-building concepts, smart charging algorithms, grid integration solutions, and interdisciplinary collaboration. These areas of investigation will be crucial for addressing the evolving challenges and realizing the full potential of renewable energy-powered EV charging infrastructure.

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