Energy Proceedings
Vol 48, 2024
ISSN 2004-2965

Viability and Advantages of Smart Hybrid EV Charging Stations: A Techno-economic Analysis#

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ABSTRACT

Transportation electrification is an important strategy of addressing the rapid growth of carbon emissions from the transportation sector. However, rapid and widespread adoption of electric vehicles (EVs) may result in adverse effects such as increased grid emissions, power equipment degradation, and reduced grid efficiency. This study employs HOMER software to develop a hybrid EV charging station model with deferrable charging, offering a potential solution to these issues. To determine the most effective energy configuration, a multi-scenario simulation using real-world charging load data is performed. Findings indicate that hybrid charging stations equipped with smart charging technology can significantly alleviate these negative impacts by reducing peak loads, cutting carbon emissions, and enhancing cost efficiency. In these simulations, the optimal solution for public charging involves integrating wind power with grid electricity. This approach yields an annual production of 1,567.5 MWh, achieves an levelized cost of energy (LCOE) of $0.051/kWh, and results in a negative net emission through the sale of excess electricity to the grid. Furthermore, comparative simulations illustrate three key points. First, the system can sell back the excess electricity to achieve a negative net emission of -266 t carbon dioxide per year. Secondly, in the public charging scenario, managed charging has a significant effect on reducing peak loads (92% reduction in the maximum peak load), lowering grid emissions by selling back excess clean electricity (-74.5t per year), and optimizing the energy cost ($0.030/kWh reduction in LCOE). Lastly, in the domestic charging scenario, on-demand charging may outperform the deferrable charging. This paper highlights the limitations of REs and smart charging, the need for region-specific strategies and energy configurations, potentially contributing valuable insights to the fields of charging strategies and energy systems.

Keywords: renewable energy resources, EV smart charging, charging infrastructure

NONMENCLATURE

Abbreviations	
EV	Electric Vehicles
LCOE	Levelized Cost of Energy
REs	Renewable Energies
IRR	Internal Rate of Return

1. INTRODUCTION

Transportation is responsible for 23% of global carbon dioxide emissions, 91% of which come from fossil fuels [1]. This will lead to the depletion of fossil energy sources and excessive emissions. The transition from internal combustion engine vehicles to electric vehicles (EV) is crucial to reduce dependence on fossil fuels, protect energy security, and reduce greenhouse gas emissions. To support the development of electric vehicles and create low-carbon transport, major economies are planning to ban ICE in some areas [1].

It is predicted that by 2040, the market share of electric vehicles in global road transportation sector will reach 11-28% [2]. Accordingly, the implementation of supporting infrastructure such as charging stations will expand rapidly. Policy support is gradually shifting towards electric vehicle supply equipment or charging stations. To support electric vehicles, governments are investing more in charging stations [1].

However, existing studies highlight several potential problems associated with the expansion of EV charging, including increased total and peak electric loads, additional emissions from power plants and grids, and fluctuations in electric loads [3]. These factors may negatively impact grid stability and economics, and adversely affect the environment. Previous research indicates that adopting smart charging strategies, REs, or energy storage facilities can effectively mitigate these negative effects [4][8].

This is a paper for the 10th Applied Energy Symposium: Low Carbon Cities & Urban Energy Systems (CUE2024), May. 11-13, 2024, Shenzhen, China.

Therefore, this study utilizes HOMERGrid to model a distributed hybrid energy charging station with deferrable charging and conduct a techno-economic analysis. Its optimization function will explore the optimal energy components, operation modes, and scales of operation. Moreover, this intelligent hybrid electric vehicle charging station is not only feasible for the case studied but can also be parameterized to suit various socio-economic and natural energy scenarios, thereby adapting to different regions and conditions.

2. MODELING & METHODOLOGY

2.1 Research framework

To explore the applicability of deferrable charging, the optimal integration of Renewable Energies (REs), and the ideal size of charging and generation infrastructures, this study leveraged and analyzed socio-economic data, natural resource metrics, and the energy supply and demand dynamics of the selected locale. A comparative analysis was conducted to ascertain the environmental and economic benefits under various load scenarios and charging strategies. The research methodology unfolds as follows: The study begins by identifying a suitable site and collecting relevant local natural resource data and socio-economic information. It then introduces variables for a range of different simulation scenarios. These scenarios are categorized by two demand patterns: public charging and domestic charging. Within each situation, two energy supply strategies are explored: managed charging and on-demand charging. The study then rigorously examines four distinct charging configurations: on-demand public charging, on-demand domestic charging, deferrable public charging, and deferrable domestic charging. After gathering the simulation outcomes, the study meticulously evaluates the environmental and economic impacts, and identify conditions conducive to optimizing benefits.

A multi-scenario analysis is conducted to examine the variations in electricity demand and supply across different contexts. In terms of charging demand, the demand curves for charging differ by region, showcasing distinct load profiles for domestic charging and public charging. Regarding the supply of REs, the capacity of natural energy resources varies, leading to differences in the generation capabilities of solar and wind power. Consequently, the variables included in this comparative study encompass domestic and public charging, various combinations of wind and solar power generation, and the presence of storage batteries. This approach enables a clear comprehension of the role of various factors within the energy system and facilitates the respectively analysis of the supply and demand sides. The research framework is shown in Fig.1.

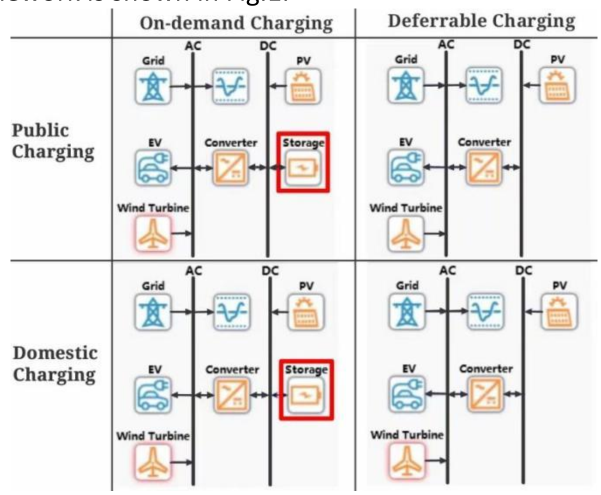

Fig. 1 Research Framework

The subsequent sections of this chapter will delve into the modeling methodology from three distinct perspectives, as outlined below:

(1) Site Selection for Charging Stations: This section will introduce the basic information of the studied location, including local natural resources, socio-economic conditions, and energy supply and demand dynamics. Moreover, an overview of some key information will also be provided.

(2) Microgrid System Design: In this part, the focus will be on the design of microgrid systems, with an emphasis on the combination of system components.

(3) Acquisition and Processing of Charging Behavior Data: This segment will provide a detailed account of the acquisition and analysis of real-world charging behaviors data, with a particular focus on the characterization of different demand patterns.

2.2 Location Selection

The researched site is Northumberland, Newcastle upon Tyne, which is set in the northeastern region of England. It lies at 54.98°N, -1.61°W within the Europe/London time zone. The region has a wealth of wind energy resources. In fact, offshore wind in Northumberland and the Northeast of England is well developed and has become a major area for offshore wind in Britain. Its wide and flat topography and long hours also provide opportunities for solar energy development. As a result, the increase in electricity demand may have a detrimental impact on the grid, which can be mitigated by the proposed EV charging station.

2.3 System components

The system components are the basic parts of the hybrid charging station. REs like solar and wind power help reduce the load on the grid and cut carbon emissions. Furthermore, batteries store renewable electricity, reducing the load fluctuations. Lastly, converters help transfer electricity between AC and DC, enhancing the system's efficiency.

This research will explore the optimal energy combination by evaluating various configurations of system components. In addition, an optimized generation capacity will be found in this research.

2.3.1 Overview of Components

PV Systems: Photovoltaic systems convert sunlight directly into electricity using the photovoltaic effect and semiconductor materials. PV Systems are now a key component of renewable energy due to its efficiency and cost-effectiveness.

Wind Turbines: Wind turbines convert kinetic energy from wind into electrical energy through rotor blades, gearboxes, and generators. Their designs vary to adapt to different environments and contribute substantially to global renewable energy production.

Storage Batteries: Storage batteries are crucial for retaining excess electricity, enhancing energy reliability and grid stability. They utilize various technologies, including lithium-ion and flow batteries.

Converters: Converters help transit between direct current (DC) and alternating current (AC), aligning energy output with grid and consumer requirements.

The integration of these components enables six primary configurations: PV/Wind Turbine/Storage, Wind Turbine/Storage, PV/Storage, PV, Wind turbine, and PV/Wind Turbine. PV systems and storage batteries are typically connected to the DC grid, with energy converted to the AC grid via converters, whereas wind turbines connect directly to the AC grid. Analyzing these configurations helps understand the role of each component and identify optimal setups.

2.4 The charging demand data

2.4.1 Demand profile of different scenarios

This section analyzes and visualizes load data recorded at charging facilities, as published by the UK government on 13 December 2018. The dataset includes 3.2 million charging events for domestic charging and data from 27 local authority charging points [6]. Two corresponding graphs for domestic and public charging are provided, illustrating distinct load profiles. The visualized load profiles from domestic and public charging demonstrate significantly different statistical characteristics. These variations are pivotal for the simulation analysis. The simulation utilizes these datasets to evaluate the performance of various hybrid energy solutions against the backdrop of differing demand patterns.

The charging behavior of EV owners can be described by the temporal distribution of three variables: charging frequency, charging power, and charging duration. The diverse charging behaviors observed in different charging scenarios give rise to a multitude of load profiles. Consequently, the planning scenarios differ due to different demand profiles.

In public charging scenario, this study utilizes data from a charging station in Northumberland County Council to simulate the impact of a smart hybrid electric vehicle charging station. Among the examined datasets, the one from Northumberland County Council is deemed the most representative, characterized by the highest number of charging events and a moderate average duration per event. Specifically, the dataset comprises 25,708 charging events, with an average duration of 35 minutes and a mean supplied energy of 7.0 kWh. The temporal distribution of these events reveals a concentration between 8 a.m. and 6 p.m., coinciding with standard working hours. Furthermore, the duration data exhibit two distinct peaks, approximately at 8 a.m. and 6 p.m., corresponding to the commencement and conclusion of typical work schedules. The charging demand of public charging is shown in Fig.2.

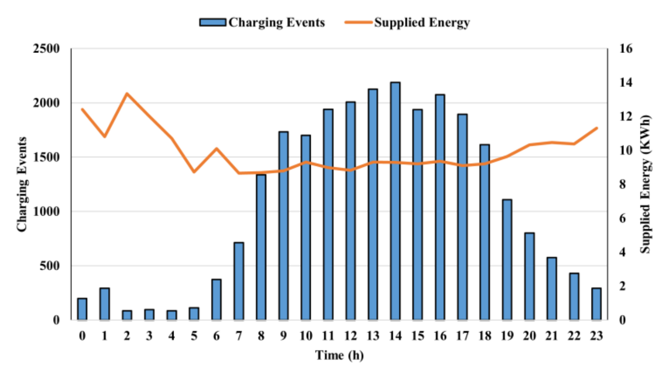

Fig. 2 Load profile of public charging

In the domestic charging scenario, the demand profile significantly differs from public charging. The mean charging time is 12:41 (hh:mm), and an average energy of 9.1 kWh is supplied in each session. Besides, a significant peak of electricity demand occurs at around 5pm in this profile, which coincides with a drop in the public charging scenario. Fig.3 shows the profile of domestic charging.

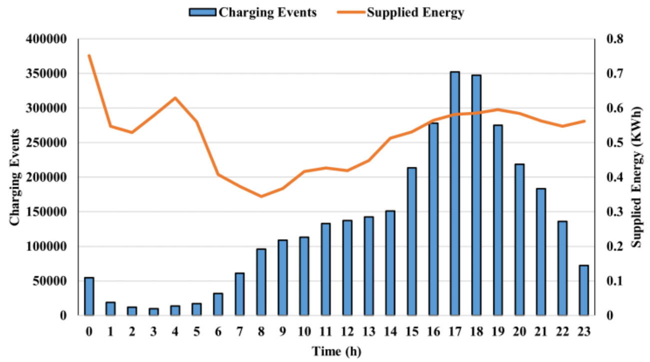

Fig.3 Load profile of domestic charging

3. RESULTS & DISCUSSION

This section will specifically describe the various outputs of the system and conduct comparative analysis. This includes exploring the applicable scenarios for managed charging, the optimal combination of REs, and the ideal scale of charging and power generation facilities.

3.1 Results

3.1.1 Public Charging

In the public charging scenario, the system simulates the most advantageous energy mix and analyses the optimal energy scale. The results of the multi-scenario simulation indicate that the optimal combination for public on-demand charging is Wind Turbine + Grid, where the optimized energy option consists of two XANT L-36 wind turbines. This system can generate 1,567.5 MWh per year, which is also the optimized generation scale. The result of public on-demand charging is shown in *Table 1.*

Table 1. Public on-demand charging

Public On-demand Charging	Annual Utility Bill Savings ($)	LCOE ($/kWh)	Carbon Emissions (t/yr)
Grid	0	0.244	465.9
Wind Turbine + Grid	376,690	0.081	-144.0
PV + Wind Turbine + Grid	377,151	0.082	-144.8
Wind Turbine + Storage + Grid	380,033	0.084	-142.6
PV + Wind Turbine + Storage + Grid	387,098	0.086	-152.2
PV + Grid	133,214	0.227	339.6

The LCOE is $0.081/kWh, resulting in an annual utility bill savings of $376,690. Furthermore, this hybrid system reduces net grid emissions by 144.0 t/yr by selling electricity back to the grid. In the public deferrable charging scenario, the optimized energy combination is also Wind Turbine + grid. However, it only requires a XANT L-36 wind turbine. The system achieves a net reduction of 218.5 t carbon dioxide per year through sellback, with an LCOE of $0.051/kWh. The outcome of public smart charging is shown in *Table 2.*

Table 3. Public smart charging

Public Deferrable Charging	Annual Utility Bill Savings ($)	LCOE ($/kWh)	Carbon Emissions (t/yr)
Grid	0	0.255	89.5
Wind Turbine + Grid	89,212	0.051	-218.5
PV + Wind Turbine + Grid	89,245	0.051	-218.6
PV + Grid	23,796	0.241	67.3

3.1.2 Domestic Charging

Domestic charging exhibits a different demand pattern than public charging, and thus may not be applicable to the same energy mix or scale.

In this scenario, the most advantageous configuration includes wind power and grid supply. This system shows a negative net emission of -165.0 t/yr, indicating a great potential for grid decarbonization. The simulation result of domestic on-demand charging is shown in *Table 3.*

Table 4. Domestic on-demand charging

Domestic On-demand Charging	Annual Utility Bill Savings ($)	LCOE ($/kWh)	Carbon Emissions (t/yr)
Grid	0	0.250	143.0
Wind + Grid	126,795	0.063	-165.0
PV+ Wind + Grid	126,795	0.063	-165.0
Wind + Storage + Grid	126,809	0.066	-165.0
PV + Wind + Storage + Grid	126,797	0.067	-165.0
PV + Grid	$533	0.250	142.6

However, it is also noteworthy that in this case, smart charging performs at a lower level than on-demand charging. While the lowest LCOE of smart charging is lower than on-demand charging, the IRR of the case is

2.13%, which may not be economically practicable. The data of domestic deferrable charging is shown in *Table 5.*

Table 6. Domestic deferrable charging

Domestic Deferrable Charging	Annual Utility Bill Savings ($)	LCOE ($/kWh)	Carbon Emissions (t/yr)
Grid	0	0.273	42.5
PV + Grid	9,541	0.260	33.4
Wind + Grid	44,964	0.046	-262.4
PV + Wind + Grid	45,355	0.048	-266.2

3.2 Discussion

This section discusses the environmental-economic contribution of REs and managed charging. It focuses on the comparative analysis of different simulation results. This will facilitate a more comprehensive understanding of the role of different energy technologies in the design of charging stations.

3.2.1 Renewable Energies

REs can generally improve the economic and environment benefit of a hybrid energy system. The electricity demand for EV charging can be partly met by REs, which reduces the energy cost of the charging station. In addition, the project can reduce the carbon emissions associated with EV charging by substituting RE for grid electricity. The electricity generated by the RE not only meets the charging needs but can also be sold back to the grid. The additional clean electricity can help reduce energy costs, with the revenue generated by selling the electricity back. In addition, the sale of clean electricity increases the proportion of decarbonized energy in the grid, thereby increasing the potential for emission reductions.

The incorporation of REs into the grid significantly enhances the economic viability. Compared to the base case where only grid power is utilized, the maximum reduction in LCOE due to renewables is $0.215/kWh. In domestic deferrable charging, the energy cost of the Wind + Grid scenario is $0.046/kWh, which represents a significant reduction of $0.215/kWh compared to the $0.273/kWh in the base case. This means that the renewable energy from the charging stations helps the grid achieve significant emissions reductions.

REs can also provide a remarkable environmental benefit. In domestic smart charging scenario, the extra electricity generated by REs is sold back to the grid. As a result, the PV + Wind Turbine + Grid system gives a negative annual net emission of up to 266.2 t carbon dioxide.

3.2.2 Deferrable Charging

In the context of public charging, regulated charging has been demonstrated to be more effective than on-demand charging. This charging strategy is superior in three key areas: peak load reduction, grid emission reduction, and energy cost reduction.

The implementation of regulated charging resulted in a 92% reduction of the maximum peak load. When on-demand charging is applied to the public charging pattern, the annual maximum load of 1179.28 kW occurs on 29 May, while the peak after the addition of regulated charging is reduced to 88.98 kW on 1 July. A comparison between the pre- and post- deferrable charging scenarios reveals that the peak load on the grid has been reduced by approximately 92%.

The applied charging strategy has the potential to reduce grid emissions by 74.5t/yr. In public on-demand charging, the charging station lowers grid carbon emissions by -144.8 t/yr, while managed charging could result in a reduction of -218.5 t/yr. The addition of regulated charging can achieve an annual net reduction of 74.5 t carbon dioxide per year, which demonstrates that smart charging can significantly reduce the emissions caused by EV charging.

Deferrable charging strategy can reduce the LCOE by $0.030/kWh. In the public charging simulation, the optimal solution for both charging strategies is Wind Turbine + Grid. A comparison of the two charging schemes in identical configurations reveals that the regulated charging scheme has an LCOE of $0.051/kWh, which is $0.030/kWh less than the $0.081/kWh of on-demand charging. This illustrates that the choice of charging strategy has a significant impact on the energy costs associated with a given total electricity demand.

Managed charging is an effective method of reducing peak loads, grid emissions, and energy costs. Nevertheless, deferrable charging does not always outperform on-demand charging. In domestic charging, regulated charging exhibits lower economic return attributes, with a project IRR of only 2.13%. This indicates that such projects are economically unviable.

4. CONCLUSIONS

This study presents a potential solution to mitigate the adverse effects associated with the rapid expansion of EVs. Simulations utilizing charging data illustrate the benefits of REs and smart charging, integrated within a hybrid EV charging station framework. However, smart charging exhibits certain situational constraints.

It is recommended that the integration of REs and smart charging strategies be prioritized to address the challenges brought about by the rapid expansion of EVs. Consistent with the conclusions of other studies [5][7][9], REs significantly reduces LCOE and carbon emissions, improving the economic and environmental sustainability of the grid. The sellback of additional decarbonized electricity allows the microgrid to achieve a remarkable negative net emission(-266t/yr) with REs. Deferrable charging results in significant reductions in peak loads, energy costs and emissions on the grid. In the simulation results, the peak load of the grid was reduced by 92%, showing a great potential to reduce the impacts of load fluctuations on grid aging and degradation, and delayed power infrastructure renewal [10]

However, given the variation in natural resources across different regions, it is essential to adapt renewable energy configurations to local conditions. The optimal energy configurations identified in the case studies are primarily based on wind energy, largely determined by its abundant wind resources. In other regions, variations in natural resources necessitate tailored energy planning configurations. Moreover, smart charging should be adjusted to suit different demand patterns. Simulations suggest that deferrable charging may encounter situational limitations due to its low economic feasibility in domestic charging scenarios.

To project future research directions, it is crucial to consider the limitations and scope of the current study. As this investigation was confined to a single region, its findings may not be universally applicable. Variations in natural resources and charging demands across different regions require customized renewable energy configurations and adaptive power supply strategies. Future research should, therefore, aim to explore renewable energy setups and smart charging strategies tailored to diverse natural conditions and charging scenarios, thereby potentially enhancing the global applicability and effectiveness of these solutions.

ACKNOWLEDGEMENT

We appreciate the financial supports from the National Natural Science Foundation of China (Nos. 72173058)

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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