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Electric Vehicle Charging Infrastructure with Hybrid Renewable Energy: A Feasibility Study in Jordan

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Abstract

Jordan Vision prioritizes the utilization of domestic resources, particularly renewable energy. The transportation sector, responsible for 49% of national energy consumption, remains central to this transition and accounts for around 28% of total greenhouse gas emissions. Electric vehicles (EVs) offer a promising solution to reduce waste and pollution, but they also pose challenges for grid stability and charging infrastructure development. This study addresses a critical gap in the planning of renewable-powered EV charging stations along Jordanian highways, where EV infrastructure is still limited and underdeveloped, by optimizing the design of a hybrid energy charging station using HOMER Grid (v1.9.2) Software. Region-specific constraints and multiple operational scenarios, including rooftop PV integration, are assessed to balance cost, performance, and reliability. This study also investigates suitable locations for charging stations along the Sahrawi Highway in Jordan. The proposed station, powered by a hybrid system of 53% wind and 29% solar energy, is projected to generate 1.466 million kWh annually at USD 0.0375/kWh, reducing CO_2 emissions by approximately 446 tonnes annually. The findings highlight the potential of hybrid systems to increase renewable energy penetration, support national sustainability targets, and offer viable investment opportunities for policymakers and the private sector in Jordan.

Keywords: cost of electricity (COE); energy consumption; electric vehicle (EV); gas emissions; hybrid system; Jordan

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1. Introduction

The global shift toward sustainable energy systems has intensified due to rising energy demand, environmental concerns, and the depletion of fossil fuel reserves. Between 2018 and 2050, global energy consumption is expected to increase by 50% [1], driving the urgent need for cleaner and more sustainable energy solutions. Renewable energy sources, particularly solar and wind, have gained considerable traction, accounting for 29.5% of global electricity generation in early 2023 [2]. However, the transportation sector, largely dependent on fossil fuels, continues to pose significant environmental and energy security challenges [3]. With this sector responsible for a substantial portion of energy consumption and greenhouse gas emissions, electric vehicles (EVs) have emerged as a promising alternative to reduce emissions and improve energy efficiency, especially when charged from renewable sources. Therefore, attention has shifted toward regulatory measures and technological improvements in the transport sector.

At this point, vehicle manufacturers have implemented fuel economy standards and improved CO_2 emission regulations globally [4]. In 2019, the European Union (EU) introduced mandatory emission reduction targets for new cars for the period 2025 to 2030 to lower greenhouse gas (GHG) emissions, providing a clear path for reducing CO_2 emissions in the transport sector. The average emissions reduction for new passenger cars is expected to be 15% by 2025 and 37.5% byn2030 [5,6]. Various technologies have been developed to reduce fuel consumption and emissions in conventional engines [7–9]. However, these measures alone are not sufficient to slow global warming and air pollution. Therefore, electric vehicles are a promising alternative to traditional vehicles powered by internal combustion engines [10,11]. Integrating EVs into transport systems can increase electricity generation emissions if the charging stations rely on traditional power plants. Consequently, the adoption of electric vehicles has become a crucial strategy to complement these measures.

Global electric vehicle adoption has experienced exponential growth over the past decade, reaching 58 million electric cars on the road worldwide by the end of 2024, up from just 26 million in 2022, an increase of over 120% in two years, as illustrated in Figure 1. Annual EV sales have also climbed significantly, with more than 18 million vehicles sold in 2023 alone, compared to 10 million in 2022 and 9 million in 2021. This surge reflects a strong shift in consumer preference toward cleaner mobility solutions and increasing support from governments and industries worldwide [12]. China continues to lead the global EV market, accounting for nearly 34 million EVs in 2024, representing more than half of the global stock. The European Union follows with 14.1 million, while the United States reached 6.3 million electric vehicles by 2024. These figures confirm that China surpassed its original target of a 20% EV market share by 2025 ahead of schedule, further strengthening its dominance in the global EV industry. China has also emerged as the global leader in electrifying buses and two-/three-wheelers, holding the largest stock share of electric buses in the world, exceeding 10%, due to the availability of a wide range of EV bus models. Many EU countries have accelerated the transition to the use of electric vehicles by setting a deadline to ban conventional diesel and petroleum car sales by 2040 [13–15]. Furthermore, developed countries have followed suit by creating regulations to integrate electric vehicles into their systems [16,17]. Overall, this demonstrates the growing global momentum toward EV adoption as part of a sustainable energy transition.

The widespread adoption of EVs introduces new pressures on electricity grids and requires the deployment of charging infrastructure that is both scalable and sustainable. Integrating renewable energy into EV charging systems presents a viable path toward low-emission mobility [17]. However, the success of this transition depends heavily on the strategic design and locations of charging infrastructure. Most electric vehicle owners prefer to charge their cars at home using a private charging station during nighttime, as almost 90% of daily trips can be completed with this option [18]. Meanwhile, private charging stations are scarce in densely populated urban areas, particularly in large cities with limited dedicated parking facilities, making access to domestic charging infrastructure challenging for most EV owners. As a result, many EV owners in such settings rely on public charging stations to recharge their cars. Additionally, on long-distance trips, on-route charging at public charging stations is necessary [19,20].

To address these challenges, the automotive and battery sectors have made significant technological advancements by offering various solutions to overcome major obstacles to mass-market sales, such as an improved deployment strategy for charging infrastructure to increase the availability of EV services [21,22]. To promote the widespread adoption of electric vehicles, it is essential to establish a public charging infrastructure or network of charging stations at a sufficient scale for commercial use. Such infrastructure enhances the availability and accessibility of charging options, alleviates concerns about the limited driving range of EVs, and allows for long-distance travel [23]. The study by [24] reports that, in 2019, the worldwide inventory of EVs amounted to 4.8 million, with China accounting for 47% and Europe for 25%. Despite a gradual growth in sales, the overall usage of EVs remains limited compared to the total number of vehicles in circulation, with only five countries having an EV market share exceeding 1.5% [23,24].

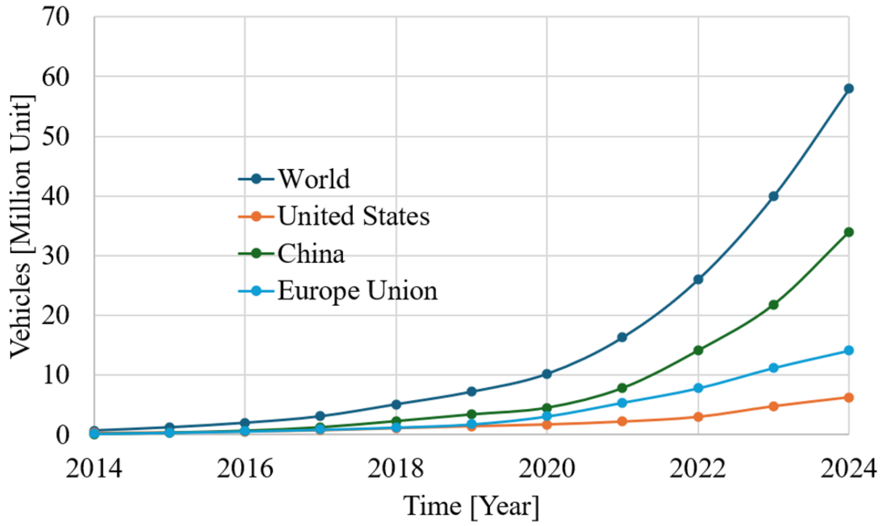


Figure 1. The worldwide inventory of electric vehicles, 2014–2024 [12].

While EV adoption is accelerating worldwide, developing countries face unique challenges in keeping pace with infrastructure demands. Jordan, for example, is experiencing rapid EV market growth, yet public charging infrastructure still lags behind [25]. At the same time, the country is endowed with abundant solar and wind energy resources, making it well-positioned to adopt renewable-powered EV charging stations [26,27]. However, few studies have addressed the integration of renewable energy systems into charging infrastructure in Jordan, particularly in remote regions.

This study addresses a gap in the planning of renewable-powered EV charging stations in underserved areas of Jordan, where infrastructure remains limited. Unlike prior studies, it integrates HOMER-based optimisation with region-specific constraints to offer a data-informed feasibility analysis. While the HOMER optimization methodology is established, the novelty of this study lies in its regional application to southern Jordan, where EV infrastructure is nearly absent, and in the integration of local solar potential, site-specific constraints, and simulated EV load profiles. This study offers practical insights to policymakers and investors seeking to promote clean transportation solutions in developing regions. To this end, this work investigates the optimal design and placement of a hybrid renewable energy-powered EV charging station along the Sahrawi Highway in southern Jordan using the HOMER software. It extends previous work [27] by evaluating performance, cost-effectiveness, and carbon reduction potential under realistic regional scenarios.

The key contributions of this study are as follows:

1. It proposes a hybrid renewable energy design (wind/solar) tailored to Jordan's highway context;
2. It analyses two operational scenarios: net purchase and zero export;
3. It quantifies economic feasibility using Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and payback period;

4. It evaluates CO_2 emissions reduction potential;
5. It recommends optimal site selection criteria for EV infrastructure expansion in remote areas.

2. Related Work

Several studies have investigated the use of HOMER software to optimise the design of EV charging stations powered by renewable energy. These studies vary in terms of location, energy source configuration, and evaluation metrics. Bansal et al. (2020) [28] designed a one-stop charging station for battery and fuel cell EVs in Denmark, combining renewable sources with grid support. Their study demonstrated that integrating renewable energy sources can meet charging demands in a cost-effective and environmentally friendly manner. Ekren et al. (2021) [6] conducted a study in Turkey that identified an optimal configuration of 44.4% wind and 55.6% solar energy for EV charging, producing 843,150 kWh annually at a cost of USD 0.064/kWh. AlHammadi et al. (2022) [29], in the UAE, developed a system using wind, solar, and battery storage, which generated surplus electricity and achieved a cost of USD 0.06743/kWh. Ampah et al. (2022) [30] in Africa proposed six 100% hybrid renewable systems combining solar, wind, and biomass to meet EV charging needs, with a payback period of approximately eight years. Li et al. (2022) [31] in China found that PV/wind/battery combinations yielded the most reliable charging station configurations, although system reliability decreased with increased EV load. Nishanthy et al. (2022) [32] applied HOMER in India to identify five highway locations for EV charging stations, obtaining a low NPC of USD 303,291 and an LCOE of USD 0.072/kWh. These studies, summarized in Table 1, reveal a consistent trend of using hybrid energy systems to balance cost, reliability, and environmental impact. However, most lack a detailed exploration of regional constraints, grid limitations, or location-specific planning, particularly in low- and middle-income countries. Moreover, none specifically address the Jordanian context or integrate HOMER optimisation with site feasibility and regional energy policies.

Table 1. Global studies using HOMER software to design charging stations.

Study (Year)	Location	Energy Sources	Load Profile	Key Findings	Limitations
Bansal et al. (2020) [28]	Denmark	Solar and Grid	Fixed daily load	Effective, eco-friendly station design	Not context-specific; no dynamic EV behavior model
Ekren et al. (2021) [6]	Turkey	Wind and Solar	Simulated daily load	44.4% wind, 55.6% solar, cost-effective	Simplified assumptions; lacks validation with real EV data
AlHammadi et al. (2022) [29]	UAE	Solar, Wind and Battery	Static demand	Surplus generation; LCOE USD 0.067/kWh	No seasonal reliability analysis and limited sensitivity testing
Ampah et al. (2022) [30]	Africa	Solar, Wind and Biomass	Fixed load scenario	Multiple system configurations; 8 yr payback	Low geographical specificity; climate assumptions not validated
Li et al. (2022) [31]	China	Solar, Wind and Battery	Steady EV load	Hybrid PV/WT/Battery most optimal	Reliability drops under high demand; no local grid policy constraint consideration
Nishanthy et al. (2022) [32]	India	Solar and Wind	Simulated daily load	Low NPC and LCOE for five strategic sites	No integration of policy context; no validation with actual charging data

Compared to these previous works, this study addresses a contextual gap by focusing on the feasibility of EV charging stations powered by hybrid renewable systems in southern Jordan, where data availability and infrastructure remain limited. It incorporates dynamic, region-specific EV load profiles, evaluates both net purchase and zero export grid scenarios, and aligns the HOMER-based optimization with local energy policies and investment considerations. Furthermore, the limitations of relying on synthetic data are clearly acknowledged and discussed in the sections below.

3. Current Landscape of Electric Vehicles and Charging Infrastructure in Jordan

The Jordanian government aims to reduce its dependence on oil sources to meet the country's energy consumption needs from 58% in 2020 to 51% in 2030 as part of its energy strategy, which emphasizes transportation electrification and the integration of renewable energy sources into the power system to achieve future energy goals [33]. The government has implemented various incentives, such as EV tax exemptions, to encourage the adoption of EVs [25]. Furthermore, in 2022, the government decided to issue 1700 charging stations in Jordan and regulate the movements of electric vehicles from both public and private stations, according to the Energy and Minerals Regulatory Commission [34].

During the past five years, Jordan has seen a substantial increase in the use of electric vehicles, a trend likely to persist due to the increasing cost of fossil fuels [35]. As shown in Figure 2, the number of EVs in Jordan has exceeded 120,000 by 2025 [25]. Amman has the highest number of registered electric vehicles, 77% of the total. Private car owners predominantly use these vehicles, and many are employed for ride-hailing services such as Uber [36]. Public agencies and service providers own a limited number of electric cars; for instance, the Royal Hashemite Court held around 150 electric vehicles in 2020, while Aramex, in the logistics sector, deployed ten electric vans. In 2023, the Jordanian government further expanded its EV fleet by purchasing 151 low-emission buses, including 15 battery-electric buses, for integration into the Amman Rapid Transit Project-marking a significant step toward electrifying public transport. While Jordan has seen a rise in EV usage, the country's infrastructure remains insufficient in terms of availability and compatibility. This scarcity presents a significant barrier to widespread EV adoption, particularly for long-distance travel in a country of Jordan's size and population [35]. By mid-2025, Jordan hosted approximately 170 EV charging stations, a substantial increase from just 87 in 2021, as shown in Figure 2. The capital, Amman, remains the primary hub, housing the majority of these stations due to its concentration of EV ownership. According to the Energy and Minerals Regulatory Commission (EMRC) and recent reports, the number of public and semi-public charging stations has steadily grown, with over 40% located in Amman alone. This development aligns with national targets to support rising EV adoption, which surpassed 41,000 registered electric vehicles in 2024 [25]. With only a few charging stations outside the capital, the existing infrastructure remains inadequate, particularly for long-distance travel. Therefore, developing a comprehensive and reliable charging network is crucial to supporting Jordan's transition to electric mobility.

The Energy and Minerals Regulatory Commission (EMRC) oversees the charging infrastructure by establishing regulations and standards, requiring approval for public charger installations, and setting electricity prices at USD 0.16 per kWh for purchase and USD 0.21 per kWh for retail.

The Jordanian EV market investment is predicted to grow by 35% from 2019 to 2025 [37], a trend that appears consistent with the increasing number of EV registrations and expanding charging infrastructure during this period. The government has implemented several strategies to encourage and facilitate electric vehicle ownership, including simplifying registration procedures, providing tax incentives to EV buyers, and expanding the charging network. Plans are also underway to introduce subsidies for EV purchases and incentivise investments through public–private partnerships [33]. Additionally, the Jordan Electric Vehicle Association (EVA), established in 2018, continues to promote and educate the public about the advantages of electric vehicles.

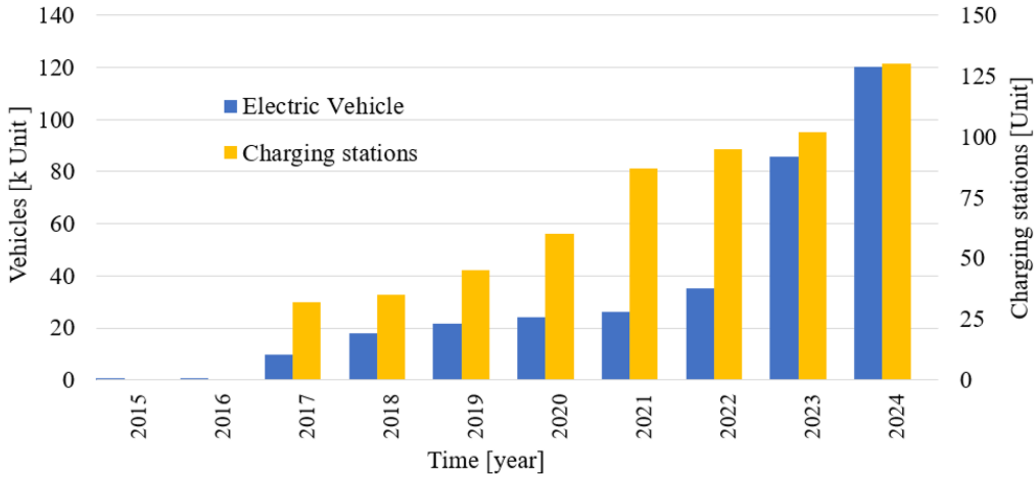


Figure 2. Illustration of the number of charging stations and electric vehicles in Jordan between 2010–2024.

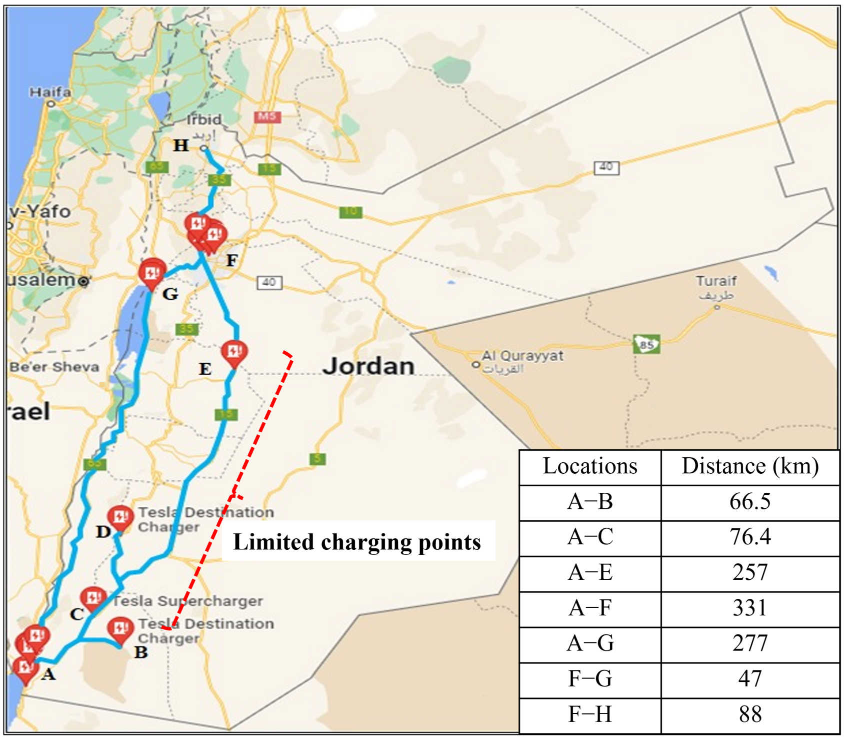
4. Site Selection Criteria for EV Charging Stations

The optimisation of charging station infrastructure generally involves two distinct approaches: a node-based approach for short trips within metropolitan areas and a flow-based approach for optimizing charging stations at the state level [38]. The flow-based model for national corridors (state-scale) charging stations takes into account several variables, such as traffic flow characteristics [39,40], demographics [39], installation costs, service quality [40,41], and vehicle range [42,43]. State-scale charging demands are primarily for long-distance travel, necessitating only fast chargers. In the study by [44], both quantifiable and non-quantifiable variables were considered to determine the optimal state-scale charging station network. Their proposed model stipulates that the maximum distance between two neighbouring charging stations should be 50 kilometres (km). The methodology presented by Csonka and Csiszár [44] is adapted here, allowing for a combination of multi-criteria point-based assessment and transportation corridor characteristics. Their approach considers both strategic and practical factors, such as traffic volume, existing infrastructure, and proximity to rest areas, to ensure accessibility and suitability for EV drivers. Based on this approach, the Sahrawi Highway in Jordan, which connects the southern and northern regions of the country, would require approximately 6–7 fast-charging stations.

The site selected in this study serves as a validated anchor point for such a future comprehensive network optimization, which would incorporate demand distribution and redundancy, as suggested by works like Loaiza-Quintana et al. [45]. The chosen Sahrawi Highway (Highway 15) is a critical South–North corridor connecting Aqaba to Amman. Its strategic importance is underscored by an annual traffic volume of over 1,825,000 million vehicles [46]. This substantial traffic flow represents the highest potential demand for long-distance travel services in Jordan, making it the most logical and data-supported corridor for the initial deployment of highway EV charging infrastructure. Siting a station here ensures that it serves the largest possible user base from its inception.

Selecting a location for an EV charging station on a highway involves several key considerations. It must be easily accessible to drivers, ideally situated at rest stops, service stations, or parking areas near exit ramps. High visibility and easy access are crucial. Electrical grid availability is also essential, as the station needs a reliable power source. Safety and security should be prioritized, with features such as surveillance cameras or good lighting to ensure visibility. Additionally, the station should be convenient for travellers, close to amenities like restaurants and restrooms, and accessible to the local community.

The site selection methodology also incorporated three key local filters: (1) locations with % electrical grid availability along the Sahrawi Highway, (2) high solar irradiation zones suitable for PV deployment, and (3) proximity to existing infrastructure to minimise construction cost and environmental impact. The study focuses on a location on the Sahrawi highway, as shown in Figure 3, which connects all Jordanian governorates. The highway stretches 331 km from Amman (F) to Aqaba in the south (A), a journey that takes about 4 h by car via this three-lane route. Currently, EV charging stations are lacking on this highway. Additionally, this corridor is a critical international land shipping route with significant renewable energy potential, including solar and wind, with varying levels of potential at different locations. The selected location was chosen not only for its high solar resource, but also for its 99% grid availability, ensuring strong grid infrastructure and minimizing interconnection cost risks. This combination directly addresses the common trade-off between resource quality and grid capacity. Therefore, the selected location ensures accessibility, renewable energy viability, grid integration, and minimal additional infrastructure cost, aligning with international best practices. This ensures the proposed station's feasibility both from a technical and economic perspective, as discussed in the next sections. This study prioritized grid availability, solar potential, and highway access as the primary feasibility filters for a proof-of-concept station. A full multi-criteria analysis incorporating land cost, safety, and amenities is recommended for future network-wide planning.



Locations	Distance (km)
A–B	66.5
A–C	76.4
A–E	257
A–F	331
A–G	277
F–G	47
F–H	88

Figure 3. Geographic locations of electric charging stations on Google Maps, including distances between critical areas.

5. Design Methodology

This study highlights the dependence of electric vehicle (EV) charging on environmental factors, utilizing solar and wind power as primary energy sources, supplemented by grid extension. The design of a solar–wind hybrid EV charging station begins by analyzing EVs' load characteristics and charging requirements and then evaluating the available solar and wind resources at the selected site. This approach ensures that the system meets demands efficiently while leveraging the local renewable energy potential. Figure 4 illustrates the overall methodology adopted in this research. The process begins with the identification of key input variables, such as the geographic and technical characteristics of the installation site, utility and EV charging parameters, cost variables related to system components (including capital, operational, replacement, and salvage costs), and environmental data such as solar irradiation, wind speed, and temperature. These inputs inform a cost–performance analytical framework that supports the simulation and optimization process.

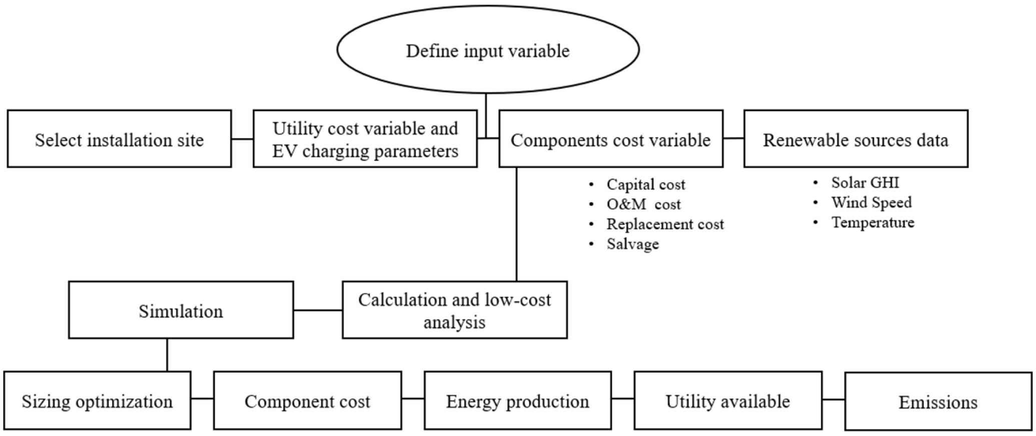


Figure 4. Methodology for optimising the system [27].

Using HOMER software, the model performs a series of simulations to evaluate multiple system configurations. The software calculates energy production, component sizing, cost-effectiveness, utility availability, and environmental impact—particularly emissions. The optimization process follows a cost-minimization strategy, identifying the most viable solution in terms of levelized cost of energy (LCOE), net present cost (NPC), and renewable energy contribution.

By integrating all of these elements into a structured and iterative workflow, the methodology provides a robust basis for identifying technically sound and economically attractive solutions for EV charging stations powered by hybrid renewable systems. This approach is adaptable, and can be replicated for other locations across Jordan by incorporating site-specific resource and economic data.

5.1. Installation Site and System Capacity

The sizing of a charging station depends on several factors, including the number of EVs, charging time, socket types, battery capacity, energy source potential, and station dimensions. It is recommended that charging stations be located outside city centers, where wind and solar energy are more viable. The station should face south for optimal solar power. Jordan currently lacks specific standards or regulations for the size of EV charging stations. According to national planning guidelines, petrol stations must occupy at least 1100 m^2 to ensure safe vehicle maneuvering and access [37]. Based on typical petrol station footprints in Jordan and to provide room for EV infrastructure layout, this study assumes a 2000 m^2 area. EV battery capacities in Jordan range from 33 kWh to 82 kWh [37]. To fully charge from one to four EVs per hour with an average capacity of 50 kWh, a production capacity of approximately 200 kWh per hour is required. Consequently, the station is designed with four fast chargers, each rated at 50 kW, consistent with common DC Level 3 highway charging standards. The system is modeled using HOMER's EV charging tool, which generates a dynamic hourly load profile based on anticipated traffic and usage patterns.

The system is designed on a commercial platform with EV charging as the primary electrical load. The 24 h load profile was generated using HOMER's built-in EV charging load modeling feature, which allows for the simulation of daily consumption based on user-defined parameters such as the number of vehicles, charging time, and peak usage windows. These parameters were set based on reasonable traffic assumptions for highway stations in Jordan, in the absence of official real-time EV load datasets. The highest electricity consumption for EV charging is 2426 kWh/day, with a peak load of 409 kW, as detailed in Table 2. The EV charging station load factor was set to 0.25 to represent typical utilization patterns, reflecting that most vehicles are charged at home or during off-peak periods. Limited simultaneous demand and partial charging for daily trips result in lower average usage, consistent with empirical data from similar studies. Variation in this parameter would substantially impact the calculated results. This peak occurs during rush hours and periods of increased human activity between 5:00–7:00 p.m. and 8:00–10:00 a.m., as illustrated in Figures 5 and 6. Due to the emerging nature of the EV market in Jordan and the lack of publicly available charging behavior data, the load assumptions were designed to reflect plausible peak demand patterns consistent with highway traffic trends and published studies from similar regions [6,29].

Table 2. Load profile of the proposed EV charging station.

Parameter	Value
Average energy (kWh/day)	2424
Average demand (kW)	101
Peak demand (kW)	409
Load factor	0.25
Sessions per day	19.7
Energy per session (kWh)	19.9
Sessions per year	7177
Annual energy served (kWh)	142,979

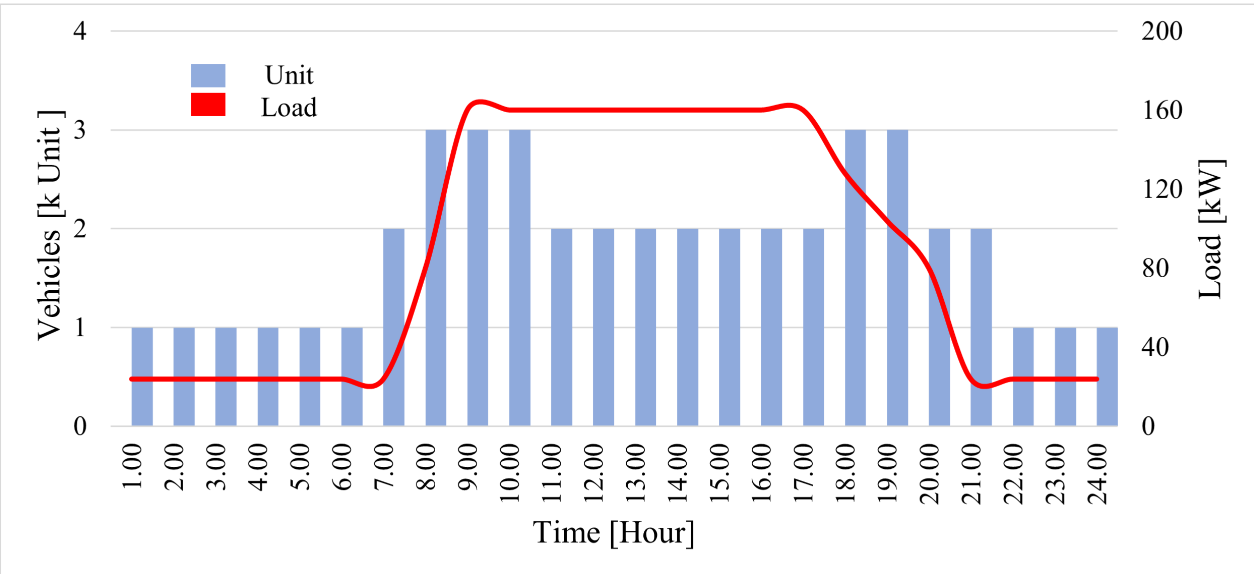


Figure 5. Predicted hourly load of the charging station.

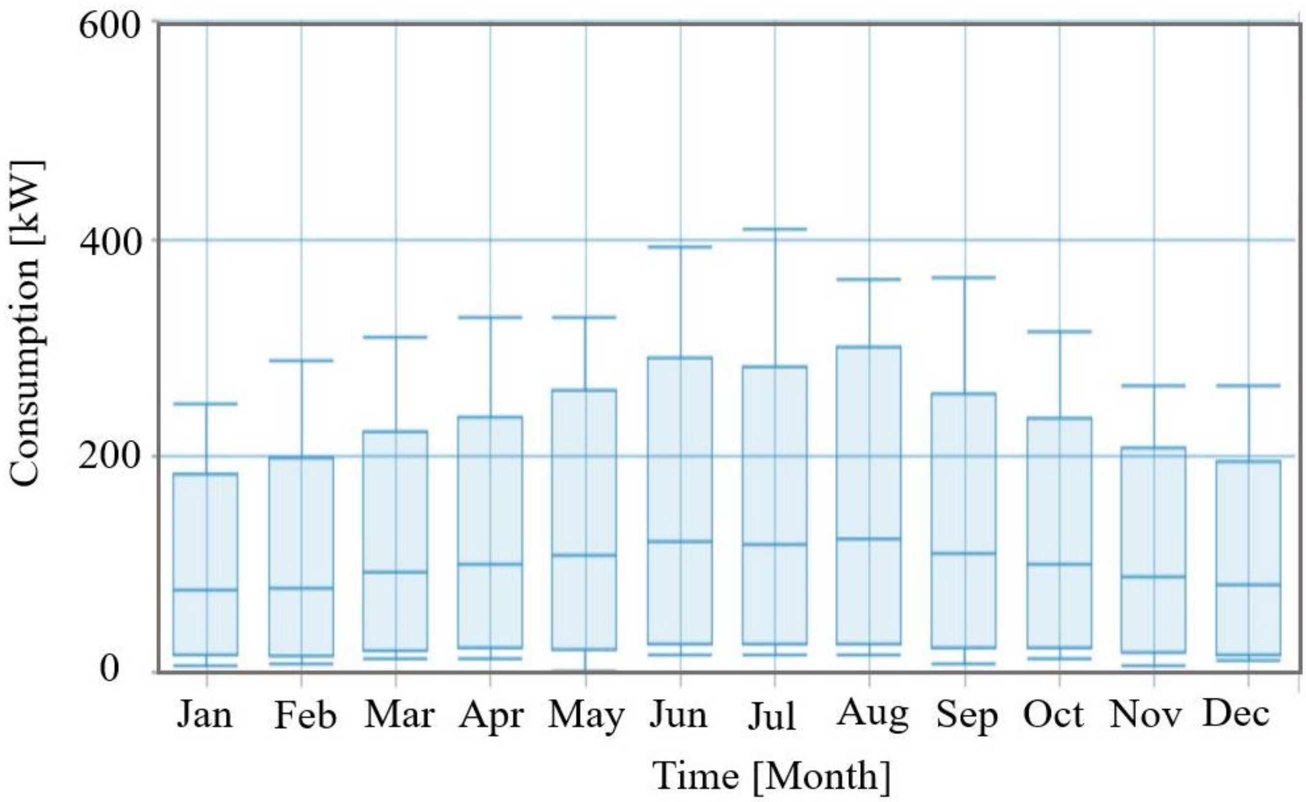


Figure 6. Predicted monthly load of the charging station.

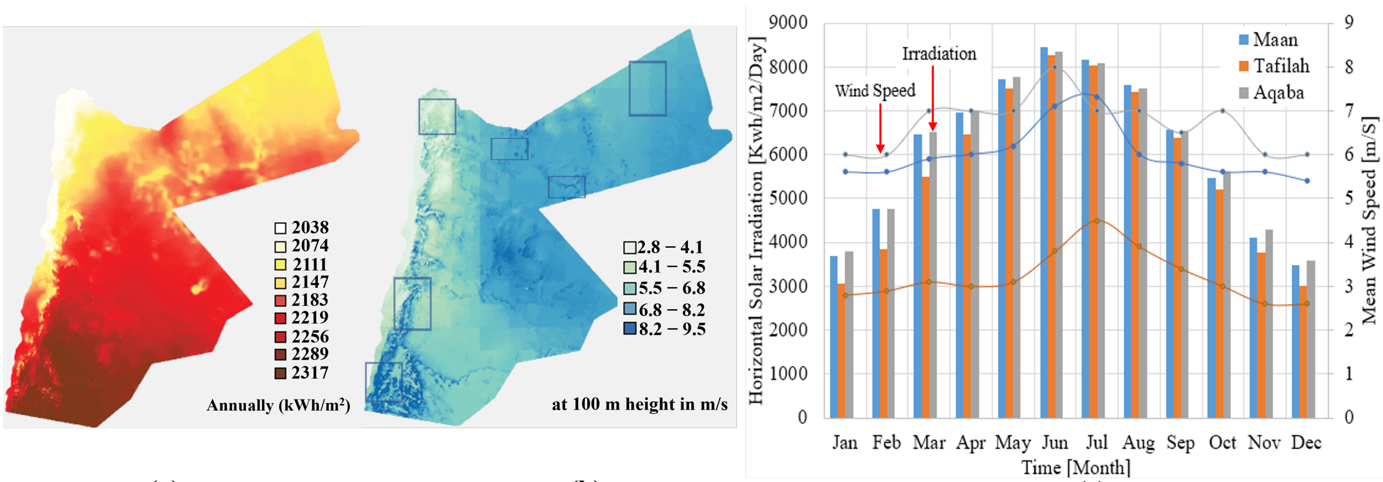
The selected site for the proposed EV charging station is located in southern Jordan, near the Ma'an governorate, along the Sahrawi Highway—approximately 170 km south of Amman at latitude 30.35° N and longitude 48.06° E. This location was identified using a flow-based methodology that prioritizes long-distance travel corridors, as discussed in Section 4. The selected site benefits from excellent solar irradiance, suitable geotechnical and hydrological conditions, and reliable access to the national electricity grid and water supply. Its position along this major north–south transport corridor ensures strategic coverage for long-distance travel, making it technically and economically viable for a hybrid renewable-energy-powered charging station.

A sensitivity analysis was performed to evaluate how changes in key parameters—such as discount rate, diesel fuel price, solar panel cost, and battery lifespan—affect the overall Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). This analysis is essential due to the inherent uncertainties in economic variables and future energy prices, especially in developing markets.

5.2. Wind Speed and Solar Irradiation of the Proposed Location

Situated within the global Sunbelt, Jordan receives high solar radiation on a horizontal surface and an average of 316 sunny days per year. This translates to a direct solar radiation intensity of 5–7 kWh/m^2 [47], placing the country among the global leaders in solar energy potential. In addition, its vast desert areas are well-suited for wind turbine deployment, with proximity to the national electricity grid facilitating integration. According to [48], around 16% of Jordan's land is suitable for wind energy generation, offering an estimated potential of 3.6 GW. Figure 7a highlights solar energy investment potential across Jordan, particularly in the southern governorates of Tafilah, Ma'an, and Aqaba. Figure 7b shows potential wind sites, while Figure 7c presents solar irradiation on a horizontal plane and wind speed at 10 m height for these governorates.

The site records an annual average of 2798 kWh/m^2 of direct normal irradiation [49]. The global tilted irradiation at the optimal angle of 28.7° for the nearby Ma'an, located at an elevation of about 1108 m, is 2578 kWh/m^2 [50]. Ambient temperature ranges from 18 °C to 24.9 °C, peaking in July and August. These months offer the highest solar radiation, with July being the sunniest month, recording 390 h of sunshine. The total annual sunshine duration in 2019 of 3517 h [33]. Table 3 summarizes the number of sunny days and sunshine hours per month in Ma'an, showing that approximately 73% of the year is sunny, reflecting a high clearness index. Wind speeds in the site typically range from 7 to 11 m/s, making it an excellent location for wind turbine deployment.



(a) **(b)** **(c)**

Figure 7. Potential solar energy and wind energy throughout Jordan. (**a**) Annual solar radiation map of Jordan, (**b**) average wind speed map of Jordan, and (**c**) solar irradiation on the horizontal plane and wind speed at the height of 10 m for the governorates Ma'an, Tafilah, and Aqaba [47].

Table 3. Distribution of sunshine days and hours per month in Ma'an, Jordan.

Month	Clearness Index	Sunshine Days	Sunshine Hours	% per Month	% per Hour
January	0.512	14.3	230	46.1	30.9
February	0.530	14.9	225	53.2	33.5
March	0.588	18.4	251	63.4	36.1
April	0.631	18.7	265	62.3	36.8
May	0.660	23.0	325	74.1	43.7
June	0.717	29.4	370	98.0	51.4
July	0.714	30.5	390	98.4	52.4
August	0.701	29.6	370	95.5	49.7
September	0.612	28.4	315	94.7	43.8
October	0.612	23.8	291	76.8	39.1
November	0.549	18.2	255	60.7	35.4
December	0.494	16.0	230	51.6	30.9

5.3. Hybrid Energy System Design

The hybrid energy system combines solar photovoltaic (PV) and wind turbines as its primary energy sources. PV modules are installed on the charging station's rooftop, while a wind turbine is placed in an area with sufficient wind potential. Electricity generated from both sources is stored in a lithium-ion battery system, ensuring a reliable power supply for EV charging during periods of low renewable generation. An Energy Management System (EMS) monitors generation and consumption, optimizes charging based on available energy, and maximizes operational efficiency. The PV system capacity is limited to 215 kW to match the available rooftop area, while the wind turbine has a rated capacity of 100 kW. Battery storage capacity is optimized using HOMER software, with constraints set between 0 and 10 kWh. Technical specifications and cost details for all components are presented in Tables 4–7.

Table 4. Technical specifications and cost information of the selected converters [51].

Parameter	Unit	Value
Capital cost	USD/unit	300
Replacement cost	USD/unit	300
Maintenance and operation cost	USD/year/unit	5
Efficiency	%	95
Lifetime	Years	15
Capacity	kW	0–1000

Table 5. Technical specifications and cost information of the selected PV panels.

Parameter	Unit	Value
Capital cost	USD/kW	1400
Replacement cost	USD/kW	1400
Maintenance and operation cost	USD/year·kW	20
Efficiency	%	19.6
Lifetime	years	25
Capacity	kW	1–215
Derating factor	%	88
Temperature coefficient of power	%/°C	−0.37
Nominal operating cell temperature	°C	45
Panel area	m^2	5.6

Table 6. Technical specifications and cost information of the selected wind turbine.

Parameter	Unit	Value
Capital cost	USD/unit	60,000
Replacement cost	USD/unit	60,000
Maintenance and operation cost	USD/year·unit	1500
Lifetime	years	20
Quantity	unit	0–2
Rated power	kW	100
Rotor diameter	m	21
Hub height	m	31.8
Cut-in wind speed	m/s	3
Rated wind speed	m/s	11

Table 7. Technical specifications and cost information of the selected batteries.

Parameter	Unit	Value
Capital cost	USD/unit	700
Replacement cost	USD/unit	700
Maintenance and operation cost	USD/year/unit	20
Lifetime	Year	10
Quantity	Unit	0–100
Nominal voltage	V	3.7
Nominal capacity	kWh	1
Roundtrip efficiency	%	85

5.4. Energy Dispatch and Management Strategy

A major challenge in solar energy systems is the mismatch between energy generation and EV charging demand, particularly the absence of PV output at night. This study evaluates two operational scenarios to address this gap: net purchase and zero export. In the net purchase scenario, surplus renewable energy is exported to the local grid, and credits are accumulated for later use during periods of low production. The energy balance resets annually, and the feasibility of this scenario relies on grid reliability and adherence to local policies. While net metering schemes do exist in Jordan, they are currently limited to specific sectors (mainly residential and small-scale commercial users) under strict capacity thresholds, typically less than 5 MW, as regulated by the Energy and Minerals Regulatory Commission (EMRC). For large-scale commercial or highway-based systems, grid feed-in permissions may be restricted [34]. In the zero export scenario, surplus energy is stored in batteries to meet demand during low-production periods, with any shortfall covered by the grid at USD 0.13/kWh. This approach is suitable where grid export is restricted or infrastructure is limited.

Recent policy updates in Jordan have improved the feasibility of grid-interactive scenarios such as net purchase. In 2024, the government lifted restrictions on large-scale renewable energy projects and introduced more flexible connection mechanisms, including net billing and wheeling [52]. Concurrently, transmission capacity has been strengthened through initiatives such as the "Green Corridor" and the new North Green substation, supported by European Bank for Reconstruction and Development (EBRD) and EU investments, facilitating the transfer of renewable electricity from southern generation sites to demand centers in the north and central regions [53]. These regulatory and infrastructure developments enhance the technical and economic viability of grid feedback, making the net purchase scenario feasible in the Jordanian context.

The proposed hybrid EV charging station architecture is illustrated in Figure 8. The system integrates PV and wind generation with the electrical grid via a converter that manages AC (grid, wind) and DC (PV, battery) flows. The lithium-ion battery system (LI ASM) smooths fluctuations in renewable generation and charging demand. The station's average daily load is 2426.45 kWh, with a peak load of 409.61 kW. Fast chargers are designed for up to 400 kW output, supporting continuous 24 h operation while prioritizing renewable inputs and maintaining grid stability.

While Figure 8 illustrates the integrated connection of renewable resources (PV and wind) with the grid and storage system, it is important to recognize the frequency stability challenges that arise when a high share of renewables is connected. In conventional weak grids without storage, penetration levels above 10–20% may lead to fluctuations and instability [54]. In the proposed design, however, this limitation is mitigated by the inclusion of a lithium-ion battery system (LI ASM) and bidirectional converters, which buffer short-term intermittency. Moreover, because the system is grid-connected, frequency regulation is ultimately supported by the national grid operator. Consequently, although the renewable share in the optimized configuration exceeds 80% [55], the reliance on storage and grid backup ensures operational stability and aligns with practical deployment considerations.

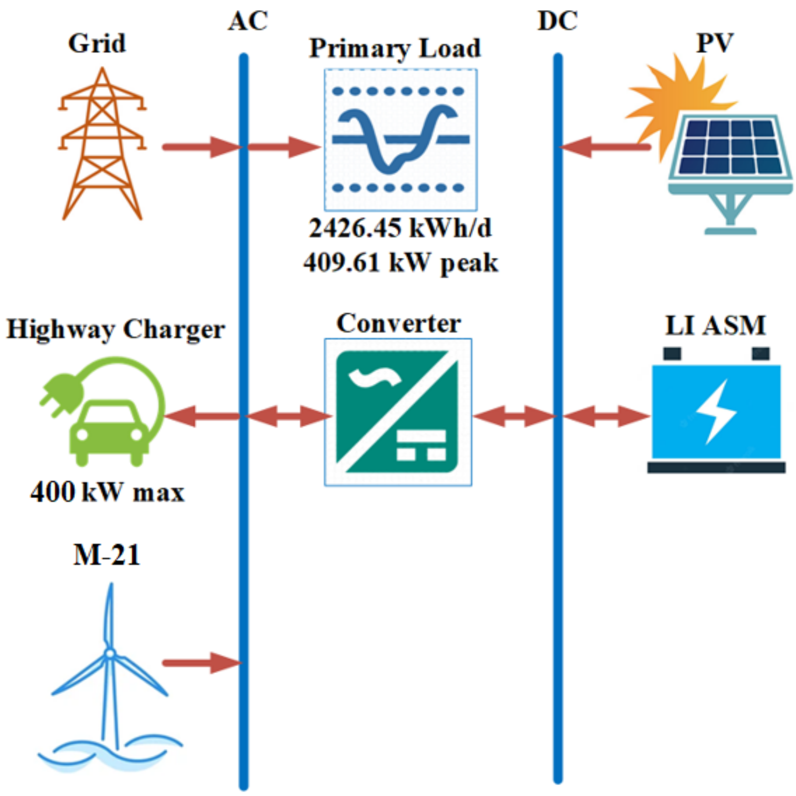


Figure 8. EV charging station diagram [27].

6. Theory and Analysis

6.1. Energy Production of the Hybrid Energy System

Several wind turbines and photovoltaic panels are available locally and can be used based on efficient results. Equation (1) determines the solar PV power output based on the inputs obtained from the solar resource page [29,32].

$$P_{PV} = Y_{PV}\, f_{PV}\, \frac{\bar{G}_t}{G_{t,\mathrm{STC}}} \Big(1 + \alpha_P\, (T_c - T_{c,\mathrm{STC}})\Big) \tag{1}$$

where Y_{PV} is rated capacity of PV system (kW), f_{PV} is derating factor (kW), $\bar{G}_t$ is PV solar incident radiation of PV array (kW/m^2), $G_{t,\mathrm{STC}}$ is standard test condition of incident radiation (1 kW/m^2), α_P is power coefficient related to temperature (25 °C), T_c is temperature of the solar cell (°C), and $T_{c,\mathrm{STC}}$ is standard test conditions of cell temperature (25 °C).

The conversion system efficiency of solar energy can be obtained by including the photovoltaic panel and other equipment efficiencies, as in Equation (2).

$$\eta_{\mathrm{sys}} = \eta_{\mathrm{PV}}\, \eta_{\mathrm{inv}}\, \eta_{\mathrm{cable}}\, \eta_{\mathrm{battery}}\, \eta_{\mathrm{other}} \tag{2}$$

Equation (3) is employed to calculate the monthly energy production of the PV panel; the monthly energy production values are then combined and fed into Equation (4) to determine the annual energy production of the PV panels:

$$E_{\mathrm{PV,year}} = \sum E_{\mathrm{month}} = H_{\mathrm{opt,month}}\, \eta_{\mathrm{sys}}\, A_{\mathrm{PV}} \tag{3}$$

A wind turbine with 100 kW capacity and a rotor diameter of 21 m is used. Therefore, the wind turbine component should assume a hub height of 31.8 m with a 20-year lifespan. HOMER utilizes Equation (4) to determine wind speed and hub height [32,51].

$$V_{\mathrm{hub}} = V_{\mathrm{ane}} \left(\frac{z_{\mathrm{hub}}}{z_{\mathrm{ane}}} \right)^{\alpha} \quad (4)$$

where V_{hub} is wind speed at hub height. V_{ane} is wind speed at anemometer height, z_{hub} is hub height, z_{ane} is anemometer height, and α is the wind shear exponent.

Equation (5) was used to estimate the yearly energy output ($E_{\mathrm{WT,year}}$) of each wind turbine located at the installation site. The calculation involved using the power curves of the turbines and the wind speeds recorded at the site. The capacity factor of the installation was determined to be 35%.

$$E_{\mathrm{WT,year}} = \text{Annual average momentary power} \times \frac{\text{hours}}{\text{day}} \times \frac{365\ \text{days}}{\text{year}} \times \frac{10^{-3}\ \text{MW}}{\text{kW}} \quad (5)$$

6.2. Optimization of EV Charging Station

HOMER was used to evaluate the energy output, environmental impact, and economic performance of the proposed hybrid system. Site-specific solar radiation, wind speed, and frequency data were input into the model, with the electricity tariff set at USD 0.13/kWh based on Jordan's grid prices [56]. Excess energy charges the battery, which then supplies EVs during low renewable output. Instantaneous load is met directly by PV generation or the grid, depending on availability and cost.

Design optimization was performed under various scenarios to determine the most effective configuration for the site. For each case, HOMER calculated the number of wind turbines and PV panels required, as well as the total rooftop area needed to accommodate the PV system.

6.3. Economic Performance Analysis

The economic analysis of the output is performed using the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE), as detailed in [7,8,57]. The mathematical analysis of NPC and LCOE has been previously discussed by the author in [27]. NPC, which represents the total system cost over its lifetime ($C_{\mathrm{t,annual}}$), is calculated using Equation (6). It includes annualized capital cost (C_{ACC}), annualized replacement cost (C_{ARC}), operation and maintenance cost (C_{AOM}), salvage value, and emissions penalties, as outlined in Equation (7). The capital recovery factor, CRF(i,n), is determined using Equation (8).

$$\mathrm{NPC} = \frac{C_{\mathrm{t,annual}}}{\mathrm{CRF}} \quad (6)$$

$$C_{\mathrm{t,annual}} = C_{\mathrm{ACC}} + C_{\mathrm{ARC}} + C_{\mathrm{AOM}} \quad (7)$$

$$\mathrm{CRF(i,n)} = \frac{\mathrm{i(1+i)^n}}{\mathrm{(1+i)^n - 1}} \quad (8)$$

In this context, n represents the project's lifetime in years, while i denotes the annual interest calculated based on the nominal discount rate. The replacement cost is included to assess the economic implications of using components with a shorter lifespan than the project's overall duration [32].

$$\mathrm{LCOE} = \frac{C_{\mathrm{t,annual}}}{E_{\mathrm{served}}} \quad (9)$$

In Equation (9), E_{served} represents the annualized electricity served, and its value can be calculated as shown in Equation (10) [29]. E_{Is} represents the electrical energy produced by the microgrid system, while E_{gr} refers to the electricity exported to the main grid.

$$E_{\text{served}} = E_{\text{Is}} + E_{\text{gr}} \tag{10}$$

The salvage of a hybrid system is determined using Equation (11) [58]. Moreover, the return on investment (ROI), which is the annual cost savings compared to the initial investment, indicating the annual cost savings in comparison to the initial investment, can be computed using Equation (12), as outlined in references [58,59]. C_{ref} represents the replacement cost of a component, and R_{comp} refers to the component lifetime:

$$E_{\text{salvage}} = C_{\text{ref}} \frac{R_{\text{comp}} - \left[n - R_{\text{comp}}\,\text{INT}(n/R_{\text{comp}})\right]}{R_{\text{comp}}} \tag{11}$$

$$\text{ROI} = \sum_{i=0}^{n} \frac{C_{i,\text{ref}} - C_i}{n\left(C_{\text{cap}} - C_{\text{cap,ref}}\right)} \tag{12}$$

6.4. Environmental Analysis

The study of carbon credits can provide environmental and economic benefits by measuring how renewable energy can reduce carbon dioxide emissions annually. In terms of the environment, it helps to determine the extent of reduction in CO_2 emissions and their impact. Carbon credits can be estimated using the method described in [29,60]. The electricity output per year of the system can be obtained as follows:

$$E_{\text{out}} = C_{\text{uf}} \times (\text{hours}) \times (\text{rating}) \tag{13}$$

where C_{uf} refers to the capacity utilization factor of the system, which is based on the renewable energy source used, and rating represents the rating of the renewable energy system. Then, the annual carbon dioxide emissions can be calculated using Equation (14). It can then estimate the yearly baseline emissions using Equation (15).

$$M_{\text{annual}} = E_{\text{out}}\, E_f \tag{14}$$

$$\text{Base}_{\text{annual}} = E_{\text{out}}\, EF_{\text{elec}} \tag{15}$$

where E_f refers to the emission factor (equal to zero in the case of renewable energy), while EF_{elec} represents the emission factor from electricity production in the region; lastly, the annual reduction in emissions can be obtained using Equation (16).

$$R_{\text{annual}} = \text{Base}_{\text{annual}} - M_{\text{annual}} \tag{16}$$

6.5. Estimation of Optimum Area for the Maximum Number of PV Panels

Photovoltaic panels were manufactured in various dimensions; hence, establishing the maximum number of panels that can fit in the designated roof area is crucial. Additionally, the shading effect must be considered when calculating the spacing between the panels. Figure 9 is used to calculate the spacing between panels, as in Equation (17) [6,61].

$$S_{\text{panel}} \geq \frac{L\,\sin(\theta_{\text{min}} - \theta_{\text{tilt}})}{\sin(\theta_{\text{min}})} \tag{17}$$

where θ_{tilt} is the tilt angle.

Assuming that there are (n) vertical modules in the installed system, each with dimensions ($L * W$) and arranged in (m) arrays, the spacing between rows is represented as D. Consequently, for a system with uniformly distributed modules, the total occupied area can be expressed as

$$A_{\text{occupied}} = n \times w \left(m \times L \cos(\theta_{\text{tilt}}) + (1 + m) \times D \right) \tag{18}$$

$$D = \frac{\cos(\theta_{\text{az}})}{\tan(\theta_{\text{elev}})} \Delta H \tag{19}$$

where θ_{elev} is the elevation angle and θ_{az} is the azimuth angle.

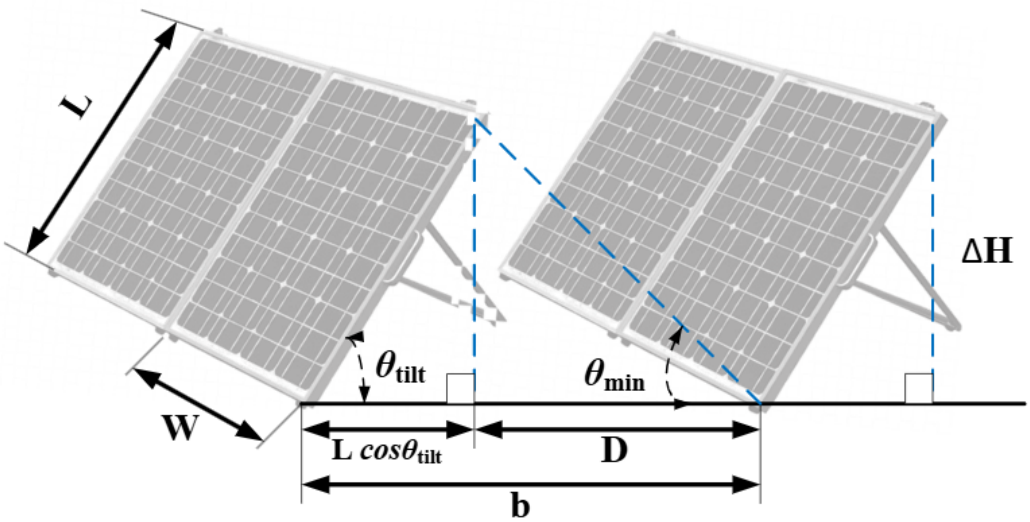


Figure 9. A visual representation of the arrangement of photovoltaic panels on a surface.

7. Results and Discussion

Building on the simulation and optimization process described in Section 6, this section presents the technical, economic, and environmental performance of the proposed hybrid EV charging station. The results are interpreted to highlight the most feasible configurations and their implications for renewable integration, cost efficiency, and carbon reduction.

HOMER was used to perform technical and economic analyses of EV charging stations powered by hybrid renewable energy sources. Four configurations were evaluated: PV-WT-Grid, PV-BAT-WT-Grid, WT-Grid, and PV-BAT-Grid. The software simulated thousands of scenarios, considering various wind turbines and PV sizes.

Figure 10 illustrates the sensitivity analysis conducted in HOMER to evaluate the relationship between the renewable fraction and the installed capacities of PV panels and wind turbines. Each point corresponds to a feasible system configuration assessed in the simulation. The figure shows that higher renewable fractions (above 80%) are generally achieved with PV capacities between 200 kW and 600 kW combined with 1–4 wind turbines. Some configurations reach up to 2.5 MW of PV and five wind turbines, but these are less frequent and likely constrained by higher costs or spatial limitations. The cluster on the right side of the plot represents the optimal configurations identified by HOMER, with the best-performing scenario supplying approximately 80% of the total station energy from renewables while maintaining techno-economic feasibility. Table 8 summarizes the optimal configuration system under net purchase conditions. While Table 9 compares the NPC of different systems. The PV-BAT-WT-Grid option achieved the highest renewable contribution (82%) and produced 1.154 GWh annually. For a zero export scenario, increasing the PV capacity is recommended to reduce reliance on grid electricity. However, this would necessitate expanding the station area to fit the additional solar panels, raising the initial investment cost by approximately USD 300,000. It can therefore be considered that net-purchase-based designs are more financially viable than those relying solely on zero export strategies.

The proposed hybrid system—two 100 kW wind turbines and 215 kW of PV—generates 1.466 GWh annually, with wind and solar contributing 53% and 29% of total output, respectively. The system operates 24/7, charges up to four EVs per hour, and costs USD 598,768 to install. With an LCOE of USD 0.0375/kWh, it is significantly cheaper than Jordan's grid tariffs (USD 0.08–0.12/kWh), especially in diesel-reliant remote areas. The payback period of 4.2 years is well below the national benchmark of 5–7 years, making it attractive for investors.

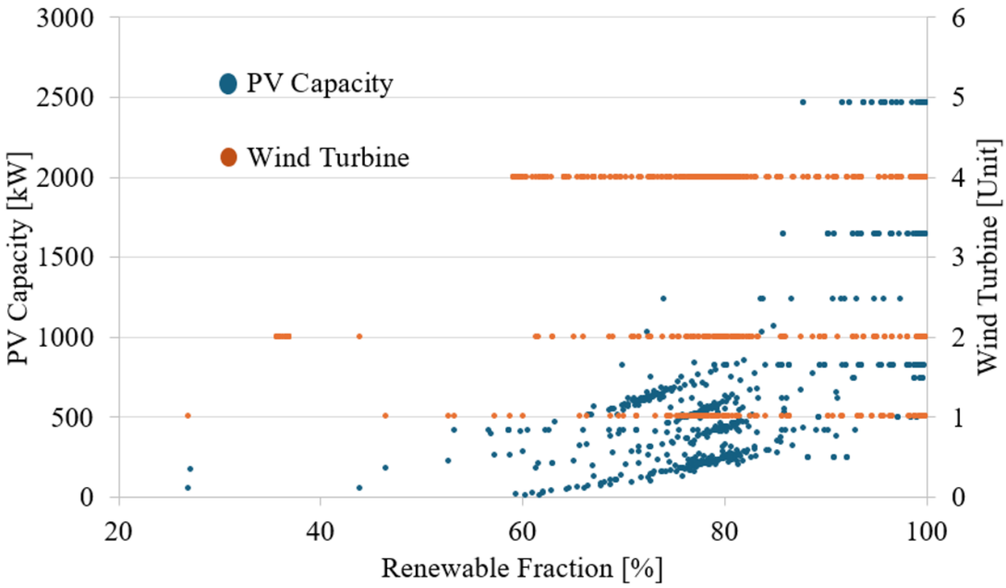


Figure 10. Sensitivity analysis of PV capacity and wind turbine numbers based on renewable fraction.

Table 8. Component sizes and economic evaluation of optimal scenarios.

Renewable System	PV (kW)	WT (Unit)	Battery (Unit)	Converter (kW)	Cost NPC (USD)	COE (USD/kWh)	Operating Cost (USD/Year)	RE (%)	Pay-Back (Years)
PV-WT-Grid	246	2	-	184	0.695M	0.0366	13,964	80.3	4.3
PV-BAT-WT-Grid	215	2	2	158	0.698M	0.0375	16,964	82.0	4.2
WT-Grid	-	2	-	-	0.783M	0.0457	43,131	59.2	2.9
Base Case	-	-	-	-	1.73M	0.13	133,722	0.00	-
PV-BAT- Grid	611	-	7	433	0.875M	0.05	13,000	72.1	5.7

Table 9. Net present cost (NPC) of the hybrid EV charging station.

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Salvage (-USD)	Total (USD)
PV	206,284	0.000	5868	0.0	212,151
WT	225,000	71,731	38,136	40,425	294,443
Battery	1400	4088	0.00	117	5070
Converter	47,478	20,143	0.00	3791	63,831
Grid	-	-	125,715	-	125,715

To validate the feasibility of the proposed system, the results were compared with similar hybrid EV charging station studies in the literature. The obtained LCOE of USD 0.0375/kWh is lower than the cost reported by [6] in Turkey (USD 0.064/kWh) and [29] in the UAE (USD 0.0674/kWh). The payback period of 4.2 years in this study is also shorter than the 8 years reported by Ampah et al. (2022) [30] in Africa. Furthermore, the renewable fraction of 82% aligns with findings by Li et al. (2022) [31] in China, who demonstrated that PV–wind–battery systems yield the most reliable outcomes under high EV loads. These comparisons confirm that the proposed design is competitive internationally and particularly attractive under Jordan's high solar potential.

The PV array covers approximately 1228 m^2, fitting within the station's rooftop area. It is important to note that the system was simulated with a discount rate of 8% and an inflation rate of 2%. Increasing the discount rate will reduce the total net present cost (NPC), meaning the higher the discount rate, the smaller the discounted value (net present value) of a future cash flow. To assess the robustness of the economic model, a sensitivity analysis was performed on key parameters such as the discount rate (6–12%), component costs (±20%), and electricity tariffs. Increasing the discount rate to 12% raised the LCOE by approximately 14%, whereas a decrease to 6% reduced the LCOE by 10%. Similarly, a 20% increase in PV module prices elevated the NPC by USD 75,000, while wind turbine cost variations had a proportionally larger impact due to their higher capital cost. These findings suggest that while the system is economically viable under baseline assumptions, financial performance is moderately sensitive to market fluctuations.

Figure 11 shows monthly generation patterns, with PV peaking in July and wind in January, while the lowest outputs occur in December and September. This resource diversity underscores the importance of hybrid designs. Figure 12 presents sample hourly outputs for February and March, highlighting the interplay between renewable generation, grid purchases, and battery operation. In both months, PV generation peaks during midday, while wind output provides a complementary, but more variable, contribution throughout the day. During nighttime hours, PV output drops to near zero, necessitating greater reliance on the grid, especially when wind speeds are insufficient. The middle plots compare system grid purchases with the baseline case, demonstrating a marked reduction in grid reliance when renewable generation and battery storage are available—most notably during peak solar hours. The lower plots illustrate the battery State of Charge (SOC), which reaches 100% during periods of surplus renewable output, particularly from the late morning to early afternoon. Stored energy is then discharged in the evening and early morning to offset low renewable supply, reducing the need for grid imports during these times. This charging–discharging pattern underscores the battery's role in balancing intermittent renewable resources with EV charging demand, ensuring continuous station operation and improving grid independence [6,29].

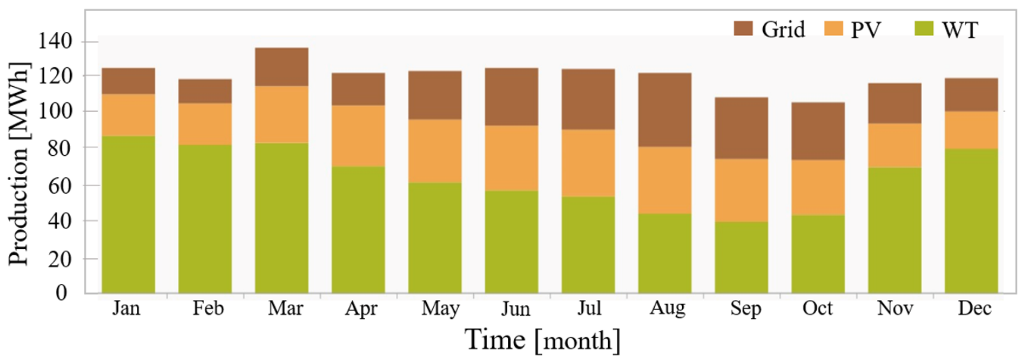


Figure 11. Electric production of the EV charging station (Case: PV-BAT-WT-Grid) [27].

The carbon reductions of each system were determined based on the annual electricity output and carbon dioxide emissions, and then the carbon credits were calculated. Figure 13 illustrates different scenarios of CO_2 emissions. Table 10 also lists the proposed emissions value for the charging station. It shows that the proposed system has outstanding carbon dioxide reduction performance, with a reduction of approximately 586 tonnes annually and up to 14,642 tonnes over the lifetime of the project (25 years). This reduction can lead to potential savings of USD 6643 annually.

Table 10. Emissions values of the EV charging station.

Quantity	Value [kg/year]
Carbon Dioxide	65,253
Sulfur Dioxide	279
Nitrogen Oxides	136

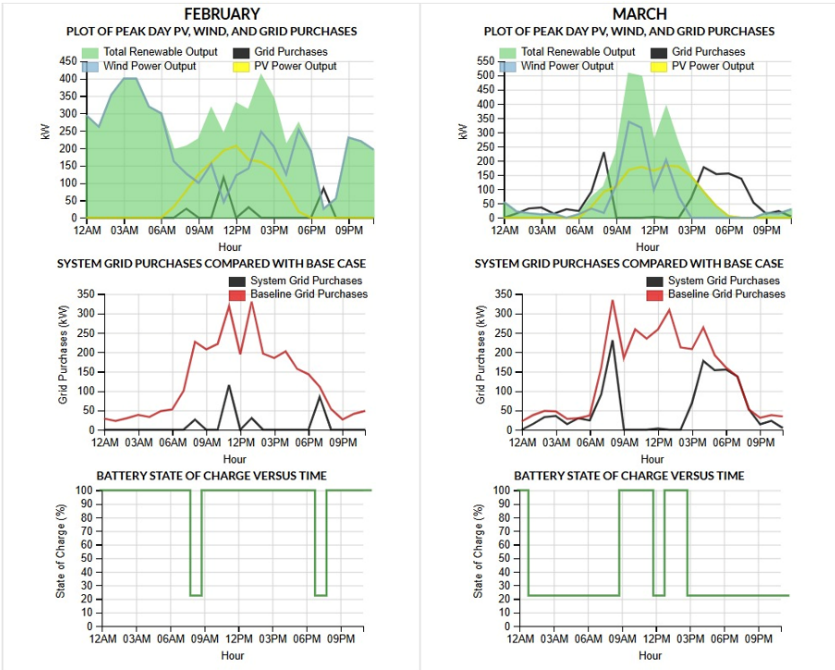


Figure 12. Renewable energy generation, electricity consumption, and battery status for February–March.

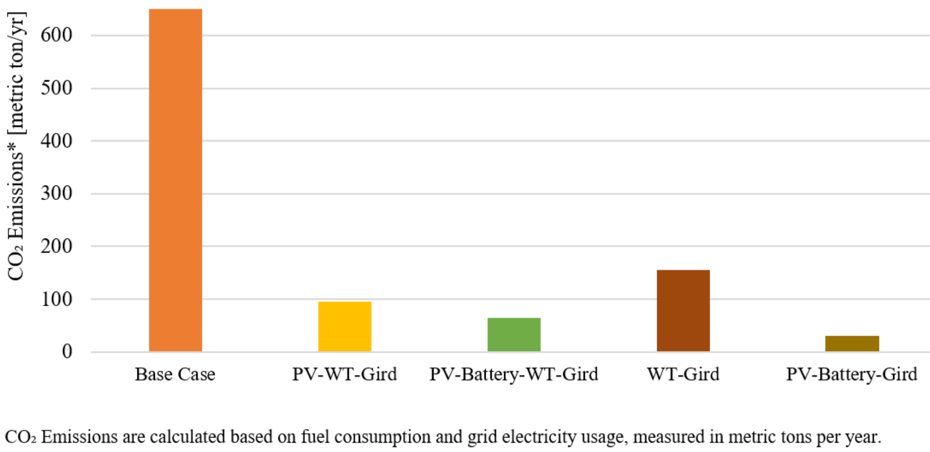


Figure 13. CO_2 emissions of various scenarios.

While this study focuses on a single-site feasibility assessment, the proposed hybrid system can be extended to a multi-location network along the Sahrawi Highway. As shown in Figures 3 and 7, most of the highway corridor offers similar renewable energy potential with only minor variations in traffic volumes. This enables the development of a distributed network of charging stations, where demand can be managed through smart control systems that direct drivers to available stations, reducing waiting times and optimizing resource utilization. Moreover, forecasts from Fitch Solutions indicate that passenger EV sales in Jordan are expected to grow at a rate of 10.4% annually through 2032, potentially reaching 40,000 units per year and accounting for more than 85% of new passenger vehicle sales [62]. This rapid market growth will place significant pressure on existing charging infrastructure, underscoring the importance of deploying a coordinated highway network. Such a network would mitigate the effects of renewable resource variability and grid constraints while improving accessibility, reliability, and long-term system resilience.

8. Conclusions

The paper focuses on areas with strong renewable energy potential, such as the Ma'an governorate, and employs HOMER Grid to design and optimize a highway electric vehicle charging station. This study analyzes various hybrid configurations, considering technical, economic, and environmental indicators. Among the assessed systems, the PV-BAT-WT-Grid configuration demonstrated the most favorable techno-economic and environmental performance, producing 1.466 GWh annually with an NPC of USD 698,000, an LCOE of USD 0.0375/kWh, and a payback period of 4.2 years. The station operates continuously with four chargers, handling approximately 20 charging sessions per day, and reduces around 586 tonnes of GHG emissions annually.

Based on these findings, this study offers practical recommendations: policymakers should prioritize supporting hybrid renewable-powered charging stations by incentivizing investment in infrastructure and offering subsidies or tax benefits. Investors are encouraged to adopt such models, particularly in high-solar-yield regions like southern Jordan, due to their favorable payback period and low operational cost. Moreover, expanding the number of chargers and integrating larger storage capacities can improve station reliability during peak demand or grid outages.

This study faced limitations due to the absence of real-world EV charging load data in Jordan or comparable regions. Consequently, a hypothetical load profile was generated using HOMER Pro's built-in EV load modeling tool, which simulates realistic daily load behavior based on defined vehicle and usage parameters. While this allows for a reasonable approximation, the model's sensitivity to load inputs is acknowledged. Furthermore, the model does not fully account for long-term component degradation or fatigue, evolving charging patterns, or future changes in grid tariffs and policy constraints, which may affect feasibility. The zero export scenario, for instance, may face implementation challenges if grid feedback is restricted under national utility policy. Future work should incorporate measured EV usage data, dynamic user behavior modeling, and long-term system performance projections, including grid integration feasibility. Additionally, Future work will expand this feasibility model into a comprehensive, GIS-based multi-criteria decision analysis (MCDA) to optimize a national charging network, incorporating factors such as land cost, detailed interconnection fees, and traffic volume. Finally, further studies should explore charging station deployment across diverse use cases—such as residential, educational, or industrial areas—where load patterns and energy availability may vary significantly.

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