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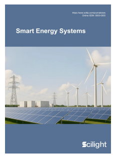

Article

Techno-Economic Assessment and Sensitivity Analysis of a Hybrid Wind–Solar EV Charging Station for Highway Applications

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Abstract: Annually, global sales of electric vehicles (EVs) are rising, and with this increase in EVs and the corresponding demand for charging, the power grid may experience shortages, or in certain regions, the infrastructure to support charging stations, particularly on highways, may be lacking. This paper explores the feasibility of using wind and solar energy along highways to power electric vehicle charging stations (EVCSs). Wind turbines can produce electricity from the wind generated by passing vehicles. When combined with solar panels installed on turbine towers or streetlight poles, they can illuminate the highway and power the EVCS located along it. This paper examines the benefits and challenges of the plan and its effects on reducing carbon dioxide (CO_2) emissions. Finally, the proposed feasibility analysis approach is evaluated on a case study of the Tabriz-Sahand highway in the Homer program, which is simulated and analyzed to build an EVCS using a combination of wind turbines, solar panels, and the grid, and the costs of different scenarios were calculated. The findings show that as electricity prices rise, the use of renewable energy for EVCS construction increases, whereas pollutant emissions decline significantly.

Keywords: electric vehicles; charging stations; wind turbines; solar panels; energy storage; highways; hybrid renewable energy

1. Introduction

The International Energy Agency (IEA) reports that the resurgence of cargo and passenger transport activities following the COVID-19 pandemic led to a 3% increase in CO_2 emissions from the transport sector relative to the prior year. Achieving the Net Zero Emissions (NZE) by 2050 goal requires an annual reduction of over 3% in transport-related CO_2 emissions by 2030 [1]. Road transport accounts for a substantial portion of fossil fuel consumption and emissions within the sector, necessitating targeted reforms to curb its environmental impact [2]. Transitioning to a cleaner transport system will require transformative changes in the sector's structure and operations [3]. The global EV market has expanded considerably; EVs are compelling alternatives to conventional vehicles [4]. The EV operating with zero carbon emissions can substantially reduce large climate impacts and pollutant emissions, and contribute to the reduction of tailpipe emissions [5,6]. The development of EVs with market competitiveness, the implementation of standardized charging infrastructure in adequate quantities, and government promotional policies all influence EV adoption [7]. Employing renewable energy and common fossil fuel power plants might alleviate this demand [8]; nevertheless, electrifying road transportation and implementing renewable energy will complicate utility distribution management [9].

With the increasing prevalence of EVs [10], wind and solar energy are among the fastest-growing technologies, projected to supply over 35% of electricity consumption by 2050 [11,12]. The 2050 net-zero forecast provides dependable and efficient energy security, fostering strong socioeconomic development and guaranteeing universal energy access [13,14]. Global registrations of new EVs reached approximately 14 million in 2023, bringing the total number of EVs on the road to 40 million, as shown in Figure 1 [15]. In 2023, EV sales increased by 3.5 million compared to 2022, representing 35% year-over-year growth [16]. This figure exceeds that of 2018, which occurred just five years ago, by more than six [17]. In 2023, weekly new registrations exceeded 250,000, surpassing the total annual registrations of 2013, a decade before. In 2023, EVs accounted for approximately 18% of total vehicle sales, up from 14% in 2022 and from just 2% in 2018 [18]. These data suggest that growth remains strong as EV markets develop [19]. In 2023, battery EVs constituted 70% of the EV inventory [20]. Integrating EVs, which produce no emissions, with low-carbon power generation technologies like wind turbines and solar PV systems can mitigate the environmental impact of harmful gases produced by internal combustion engine (ICEs) [21]. The effectiveness and reliability of these integrated systems depend on various influential factors. Multiple parameters govern the technical and economic feasibility of renewable energy-based EV charging systems. For example, Ye et al. [22] analyzed a solar-powered EV charging station and highlighted the significant influence of interest rates on the cost of energy (COE), noting that an increase in the interest rate from 0% to 6% raised the COE from $0.027/kWh to $0.097/kWh. The growing adoption of EVs presents environmental challenges, particularly regarding electricity demand. As the number of EVs increases, their substantial energy requirements could impose significant stress on power grids [23]. To mitigate these impacts, it is essential to explore low-emission electricity supply solutions. Integrating renewable and clean energy technologies into power generation for EVCSs offers a viable approach to reducing emissions and enhancing the environmental sustainability of EV systems [24].

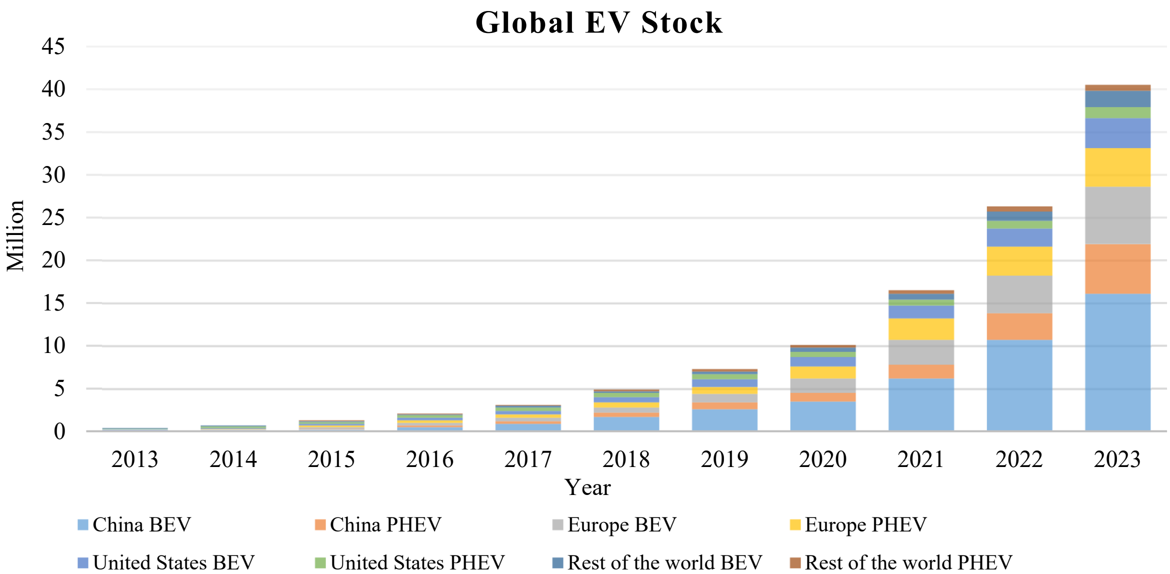

Figure 1. Global electric vehicle stock from 2013 to 2023 (Adapted from [16], © 2024 International Energy Agency (IEA). Licensed under CC BY 4.0).

Numerous obstacles exist in the deployment of EVCS [25]. The daily increase in the number of vehicles on the road necessitates greater electrical power consumption [26]. This will exert pressure on the grid to deliver increased electrical power. This could overburden the grid, necessitating increased power generation, especially if it is derived from fossil fuels, which could cause environmental damage comparable to that of ICE vehicles [27]. Additionally, grid overcrowding may lead to voltage fluctuations. This could lead to regulatory concerns, voltage instability, and a surge in peak demand [28]. The system's reliability and efficiency will decline, leading to a significant increase in thermal stress. The loading will increase, and the most significant impact will be observed in load forecasting [29]. Given that most EVCSs draw their energy from the grid, which increases grid electricity consumption and poses network challenges [30], this paper examines the feasibility of using renewable solar and wind resources to supply the energy required for EVCSs on highways and discusses their advantages. The study also examines the recently established 22-km highway from Tabriz to Sahand in Iran. We examine the feasibility of establishing an EVCS on this roadway, using wind turbines and solar panels integrated along the same highway. Ultimately, we simulate this microgrid using the Homer software.

2. Research Gaps & Contributions

There are several research gaps around EV charging stations and renewable energy sources, which include:

- ✓ Limited studies addressing hybrid wind–solar planning specifically for highway EV charging corridors.
- ✓ Insufficient integration of vehicle-induced wind turbines with PV systems in EVCS feasibility studies.
- ✓ Electricity-price sensitivity analysis for long-term feasibility in regions with subsidized energy markets.
- ✓ Limited discussion of renewable penetration transition thresholds under dynamic pricing scenarios.
- ✓ Absence of emission–economic coupled analysis for highway-based EVCS planning.

The main contributions of the current study are listed as:

- Techno-economic optimization of a hybrid wind–solar–grid EVCS along a real 22 km highway corridor.
- Integration of vehicle-induced wind turbines (ENLIL-type VAWT concept) with PV systems.
- Long-term (20-year) economic modeling using HOMER Pro.
- Structured electricity price sensitivity analysis ($0.002–$0.5/kWh).
- Renewable penetration transition analysis (0% to 96%).
- Emission reduction quantification (CO_2, SO_2, NO_x).
- Policy-relevant analysis for subsidized vs. market-based electricity systems.

3. Literature Review

Solar and wind energy have emerged as significant solutions for providing electrical power in rural and off-grid areas because of recent developments in power electronic storage systems and decreasing component costs [31,32]. Solar and wind energy are abundantly available in nature and offer greater advantages compared to alternative power generation options [33]. Despite the availability of substantial research findings on EV/BEV, there is a paucity of studies concentrating on large-scale renewable energy planning [34]. Notably, only a limited number of studies focus on solar and wind energy planning for extensive transportation systems, such as national highways [35]. Currently, there is insufficient research on hybrid renewable energy planning for national highways accommodating diverse battery EVs that are in continuous motion, with some necessitating battery recharges en route to complete their trips [36]. In contrast to other renewable energies, solar and wind energy are accessible worldwide [37]. Nonetheless, they differ from conventional electricity in terms of availability; specifically, they are typically accessible throughout a region in a decentralized manner. Furthermore, their availability is sporadic throughout the day, with supply amounts fluctuating from one day or season to another, occasionally exhibiting substantial variance. Furthermore, due to regional climate variations, a specific solar/wind energy combination may not be optimal for all charging sites within the transportation network [38]. The disparities present significant issues for policymakers, as identifying suitable areas for battery EVs to recharge using locally generated renewable energy is challenging, specifically electricity produced by nearby solar panels or wind turbines [39]. This location-sizing problem presents an additional challenge due to the potential requirement for grid-scale battery installations at some charging sites, necessitating the storage of sufficient solar or wind energy for future utilization [40].

These arguments provide ample motivation for this research paper. The goal is to find a reasonable approach for implementing suitable solar and wind at designated sites to facilitate the electrification of highway vehicles using renewable energy. The transportation network requires strategically placing charging stations with suitable capacities to accommodate EVs [41]. These facilities involve substantial investments, including costs related to charging infrastructure, installation management, and power utility connections [42]. Each 150 kW super-fast charger costs between 76,000 USD and 100,000 USD, impacting economic activities and potentially causing traffic issues if not adequately planned. Poorly designed infrastructure can lead to significant economic losses. Consequently, this challenge has attracted global attention, resulting in the development of various solution strategies tailored to different contexts [43]. Among all location-sizing challenges, addressing the needs of interstate travel is perhaps the most complex. This type of travel requires EVs to cover long distances, necessitating "en-route charging" to mitigate range anxiety [44]. As the global shift toward EVs accelerates, the demand for charging infrastructure is increasing and will likely continue growing exponentially. This trend underscores the urgent need to expedite the development of charging networks and conduct location-sizing analyses within a multi-period context [45].

The comparison in Table 1 demonstrates that although previous studies have investigated renewable-based EV charging systems, most focus on urban or generic applications, PV-only configurations, or technical feasibility without structured long-term economic sensitivity analysis. Very few works address hybrid wind–solar systems in highway corridors, and none integrate vehicle-induced wind energy harvesting with electricity price-driven feasibility evaluation and emission quantification over a 20-year lifecycle. The present study differentiates itself by combining (i) highway-based hybrid renewable generation, (ii) vehicle-induced wind turbine integration, (iii) structured electricity price sensitivity analysis, (iv) long-term techno-economic optimization, and (v) environmental emission assessment within a unified modeling framework.

Table 1. Structured comparison of related studies on renewable-based EV charging systems.

Ref.	Energy Sources	Application Context	Methodology	Economic Indicators	Sensitivity Analysis	Emission Analysis	Key Limitation
[32]	Solar–Wind Hybrid	Grid-connected EVCS (general)	Technical simulation & sizing	LCOE	No	Limited	No highway-specific modeling; no price sensitivity
[33]	Solar PV	Nano-grid EV charging	Technical review & modeling	Not comprehensive	No	No	Focused on PV-only; lacks hybrid integration
[35]	Renewable-based EV charging	General EV infrastructure	Comprehensive review	Not applicable	No	No	Conceptual review; no case study optimization
[42]	Solar–Wind	Highway electrification	Sustainability assessment	Limited cost metrics	No	No	No long-term economic optimization
Present Study	Vehicle-induced Wind + Solar + Grid + Storage	22-km Highway EV Charging Corridor	Long-term techno-economic optimization using HOMER Pro	NPC, LCOE, Total Cost, Replacement & Salvage	Yes (Electricity price: \$0.002–\$0.5/kWh)	Yes (CO_2, SO_2, NOx)	Deterministic profiles (stochastic modeling suggested for future work)

4. Innovative Wind Energy Solutions

In recent years, interest in harnessing energy from renewable sources has significantly increased [46]. Among the many factors driving this trend, economic considerations are paramount. A well-designed wind energy harvesting system can generate substantial renewable electricity with zero carbon emissions [47]. The prospect of ongoing energy collection, independent of wind strength, is especially intriguing. This can be accomplished, among various techniques, by employing turbines that harness wind produced by the motion of vehicles [48].

In this paper, we propose using solar panels and wind turbines to supply the electricity required for EVs on highways. Similar to the approach examined by Arunachalam Sundaram et al. [49], which assessed the feasibility of using vertically mounted turbines on highways to power street lighting, we suggest applying the same method to meet the energy needs of EVCSs. With more than 1.475 billion vehicles traversing worldwide roads, the airflow they create offers a significant chance for energy generation [50]. Small and effective wind turbines can be positioned alongside roads, in the center dividers of highways, or even elevated above roadways to capture this energy efficiently.

Horizontal-axis wind turbines (HAWTs) are occasionally mounted on wind stands to capture energy from winds created by moving vehicles [51]. In contrast, vertical-axis wind turbines (VAWTs) are more frequently utilized, including multi-blade Banka turbines along with various designs of Savonius and Darrieus turbines [52]. The energy collected from these turbines is typically stored in energy storage systems (ESSs) and later utilized to energize road infrastructure, such as streetlights along highways. This approach could similarly be employed to recharge EVs. In a particular study [53], researchers implemented a two-dimensional (2D) computational fluid dynamics (CFD) model to assess the effectiveness of a Banka wind turbine situated near a roadway [54]. They investigated how vehicle speed, the spacing between vehicles, and the turbine influenced the energy output of a VAWT. The findings revealed a decline in VAWT efficiency as vehicle speed and distance increased [55]. Nonetheless, the constraints of the 2D model may lead to computational errors. Lapointe and Gopalan also employed a 2D CFD model to assess the functionality of small wind turbines positioned above highways. Their investigation concentrated on events occurring on a plane that is perpendicular to the surface. They examined a commercial helical HAWT model functioning in high-traffic scenarios, but their assumptions and simplifications regarding vehicle dynamics were markedly different from actual conditions [56]. Data from another research study [57] indicated that the average rise in wind speed at a baseline wind velocity of 6 m/s was 1.8 m/s for light vehicles and 2.4 m/s for heavy trucks. Determining the ideal turbine design for optimal efficiency is crucial, which is why various types of wind turbines and blades are utilized according to particular environmental and meteorological factors. Research presented in [58] indicates that the helical turbine excels in harnessing energy from wind currents produced by moving vehicles. This turbine configuration showcases significant starting torque and initiates function at minimal wind velocities, even when under load. Its design guarantees a steady driving torque during its complete rotation, thereby improving overall efficiency [59].

Another approach involves installing ENLIL setups on highways to harness energy from bidirectional traffic. Vehicles traveling at high speeds generate sufficient wind to continuously operate these turbines. Research [60] found that a small-scale vertical axis turbine can produce a power output of 5.7 kW at a wind velocity of 20 m/s and 7.1 kW at 25 m/s [61].

The Alpha 311 turbine's compact size, lightweight construction, and innovative shaftless design allow it to be deployed in almost any location. The turbine operates at optimal efficiency when placed near a road or railway, as it captures airflow generated by passing vehicles, producing energy even in the absence of natural wind. An advanced sensor array collects localized atmospheric data to enhance performance. These turbines are mounted on existing street lighting columns along roadways, enabling them to harness the significant, untapped energy produced by moving vehicles. The turbine is specifically designed to capture and utilize air movement created by passing automobiles. According to Thompson, a compact vehicle traveling at 50 mph displaces air at approximately 12 mph—sufficient to drive the turbine's rotation. When installed on highways, each turbine can generate, on average, 30 times the power output of a 300W solar panel, which is equivalent to the output of about 14 panels mounted on a building [62].

Fundamental Equations for Wind Turbine Efficiency

Numerous designs of wind turbines are available, primarily divided into two categories: HAWTs and VAWTs. A crucial characteristic that defines a wind turbine is the power coefficient C_p:

$$C_p = \frac{P_t}{P_W} \tag{1}$$

Characterized as the proportion of turbine power P_t:

$$P_t = \frac{\rho}{4} A(V_1^2 - V_2^2)(V_1 + V_2) \tag{2}$$

To the overall power generated by wind, P_w:

$$P_w = \frac{1}{2}\rho A V_1^3 \tag{3}$$

Taking into account the variables of air density (ρ), the area (A) of the pertinent wind stream, and the wind velocities at (V_1) and (V_2) for the turbine. By substituting (2) and (3) into Equation (1), the resulting expression is derived:

$$C_P = \frac{1}{2}(1 - \frac{V_2}{V_1})^2(1 + \frac{V_2}{V_1}) \tag{4}$$

C_p is also known as the Betz Limit.

By examining the extremum of this coefficient in relation to V_2/V_1, one can determine the optimal change in wind speed flowing through the turbine to enhance power extraction from wind energy. The peak power, which is 16/27 of the total energy carried by the wind, is realized when (V_2/V_1 = 1/3) [63]. The coefficient C_p is affected by various elements, including the turbine's rotational speed, the instantaneous wind velocity, and design features such as the quantity and shape of the blades. In horizontal-axis turbines, it is also influenced by the current angle of the turbine blades [58].

5. Solar Panels

Implementing PV systems on highways—such as placing solar panels on vertical-axis turbines or light poles—holds great promise for enhancing renewable energy production and promoting the use of sustainable resources. Several pilot projects in China, the United States, Germany, Austria, and Switzerland have already demonstrated the technical feasibility of using PV systems to supply electricity for highway rest areas and tunnels [64].

These projects highlight two main advantages of roadway photovoltaic systems. First, these systems can significantly reduce CO_2 equivalent emissions by generating renewable electricity that can be integrated into the grid and used for charging EVs, thereby conserving energy that would otherwise be derived from fossil fuels. Second, they help mitigate energy loss and promote more efficient use of available resources. The United States has an extensive roadway network covering 6.6 million kilometers, including the interstate highway system and various state, county, and local roads [65]. Allocating highway areas exclusively for photovoltaic panels could generate substantial amounts of renewable electricity, significantly reducing carbon emissions and contributing to the goal of achieving a net-zero emissions future.

6. The Selection Criteria for Key Model Predictive Control (MPC) Parameters

6.1. Prediction Horizon (Project Lifetime and Operational Horizon)

In this study, the prediction horizon was defined using a two-level structure to ensure both economic accuracy and operational realism of the system. At the long-term level, a 20-year project lifetime was selected, which is consistent with the typical lifespan of photovoltaic systems (approximately 20–25 years), the operational lifetime of wind turbines (around 15–20 years), and standard practice in techno-economic assessments of hybrid microgrids. This long-term horizon enables accurate calculation of key economic indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), replacement costs, and salvage value. At the short-term operational level, the simulation was conducted with an hourly time resolution over a full year (8760 h) to accurately capture daily and seasonal variations in solar irradiance, wind speed, and EV charging demand. This dual-horizon framework ensures that the system evaluation remains economically robust while maintaining realistic operational representation.

6.2. Weighting Criteria (Economic vs. Renewable Contribution Trade-Off)

In this study, instead of employing explicit quadratic weighting matrices as typically used in classical MPC, the system objective is formulated through techno-economic optimization within HOMER Pro, where the primary goal is the minimization of total NPC subject to technical and operational constraints. The implicit weighting between renewable energy utilization and grid dependence emerges naturally from this cost-minimization framework. The optimization is constrained by predefined limits on renewable penetration, battery state-of-charge (SOC), grid purchase and sales capacity, and selected dispatch strategies (load-following or cycle-charging). In the base scenario, where the electricity price is set at $0.002/kWh, the model prioritizes grid electricity due to its economic advantage. However, as demonstrated in the sensitivity analysis (with electricity prices increased up to $0.1–0.5/kWh), the optimization dynamically shifts toward higher renewable energy integration. Renewable penetration increases progressively from 0% to 96% as grid electricity prices rise, clearly indicating that the relative “weighting” between renewable and grid resources is not arbitrarily imposed but is an endogenous outcome of economic optimization under defined technical constraints.

6.3. Battery Dispatch Strategy (Control Equivalent to MPC Penalization)

The battery dispatch strategy was defined based on technical reliability requirements and lifecycle cost considerations rather than arbitrary control penalties. Operational constraints include predefined SOC limits to prevent overcharging and deep discharge, manufacturer-recommended cycling thresholds, replacement cost parameters, and reliability requirements associated with Level 3 (DC fast) EV chargers. These constraints ensure stable power delivery during fast-charging periods, mitigate excessive cycling degradation, and provide realistic long-term economic evaluation of storage performance. By explicitly incorporating these operational limits into the optimization framework, the model achieves a balanced trade-off between reliability, durability, and economic efficiency. The revised manuscript now clearly specifies the adopted SOC bounds, cycling assumptions, and replacement cost parameters to enhance reproducibility.

6.4. Sensitivity Analysis as a Robustness Validation Tool

To ensure robustness and avoid dependence on a single economic assumption, a structured sensitivity analysis was conducted by varying electricity prices within the range of $0.002 to $0.5 per kWh. This range reflects both current subsidized electricity conditions in Iran and potential future market-based pricing scenarios. The results demonstrate a logical transition from grid-dominant operation under low electricity prices to renewable-dominant configurations as prices increase. This systematic variation confirms that system behavior is economically driven rather than manually tuned. Therefore, instead of defining fixed weighting matrices, the model allows market-based price signals to govern the optimal configuration and dispatch strategy, ensuring methodological transparency and economic consistency.

6.5. Equations

Based on Equation (5); the efficiency of the solar panel is employed. After determining the system efficiency; the monthly energy output for the selected photovoltaic panel was calculated using Equation (7). By aggregating all these monthly energy outputs; the annual energy production of the chosen photovoltaic panels in the installation region was evaluated using Equation (8).

$$\eta_S = \eta_{PV} \cdot \eta_{Inverter} \cdot \eta_{cable} \cdot \eta_{other} \cdot \eta_{battery} \tag{5}$$

$$H_{\text{opt},m} = H_{\text{opt},d} \cdot N_{\text{day}} \tag{6}$$

$$E_m = H_{opt,m} \cdot \eta_s \cdot A_{PV} \tag{7}$$

$$E_{y,s} = \sum E_m \tag{8}$$

η_S: Overall system efficiency, incorporating the efficiency of photovoltaic panels (η_{PV}), inverter ($\eta_{Inverter}$), cables (η_{cable}), other losses (η_{other}), and battery efficiency ($\eta_{battery}$). This parameter represents the total efficiency of the energy generation and distribution system.

$H_{opt,m}$: Optimal monthly solar irradiation, calculated as the product of the average daily solar irradiation ($H_{opt,d}$) and the number of days in a month (N_{day}).

E_m: Monthly energy generated, dependent on the monthly optimal solar irradiation ($H_{opt,m}$), the overall system efficiency (η_S), and the surface area of the photovoltaic panels (A_{PV}).

$E_{y,s}$: Annual energy generated by the system, which is the sum of the monthly energy production ($\sum E_m$).

The sizes of the solar panels intended for optimization differ from each other. Therefore, it is crucial to determine the highest number of photovoltaic systems. Panels that can be installed on the specified roof space. A spacing between photovoltaic panels must be computed while taking into account the impact of shading. The steps for this calculation are outlined in Equations (9) to (17) below [66].

$$\theta_z = 90 - h \tag{9}$$

$$cos\omega_{ew} = \frac{tan\delta}{tan\Phi} \tag{10}$$

$$C_1 = \begin{Bmatrix} 1 & if\,|\omega| \le \omega_{ew} - 1 \\ 0 & if \rightarrow \omega > \omega_{ew} \end{Bmatrix} \tag{11}$$

$$C_2 = \begin{Bmatrix} 1 & if\,(\Phi - \delta) \ge 0 - 1 \\ 0 & if \rightarrow (\Phi - \delta) < 0 \end{Bmatrix} \tag{12}$$

$$C_3 = \begin{Bmatrix} 1 & if\,\omega \ge 0 - 1 \\ 0 & if \rightarrow \omega < 0 \end{Bmatrix} \tag{13}$$

$$sin\gamma'_S = \frac{sin\omega cos\delta}{sin\theta_Z} \tag{14}$$

$$\gamma_S = C_1 C_2 \gamma'_S + C_3 \left(\frac{1 - C_1 C_2}{2}\right) 180 \tag{15}$$

$$tan\chi_{min} = \frac{tanh}{cos\gamma_s} \tag{16}$$

$$b \ge \frac{a \cdot sin(\chi_{min} + \beta)}{sin\chi_{min}} \tag{17}$$

θ_z: Solar zenith angle, derived by subtracting the solar altitude angle (h) from 90°.

ω_{ew}: Solar east-west angle, calculated as the ratio of the tangent of solar declination ($tan\delta$) to the tangent of geographic latitude ($tan\Phi$).

C_1, C_2, C_3: Logical coefficients that define various conditions for solar radiation and the sun's position:

C_1: Takes a value of 1 or 0 depending on whether the hour angle (ω) is less than or equal to the east-west angle (ω_{ew}).

C_2: Takes a value of 1 or 0 depending on the difference between the slope angle (Φ) and the solar declination (δ).

C_3: Takes a value of 1 or 0 based on whether the hour angle (ω) is positive or negative.

γ_s: Shading angle, calculated using the logical coefficients (C_1, C_2, C_3) and the sun's position.

χ_{min}: Optimal shading angle, obtained as the tangent of the shading angle divided by the cosine of the shading angle ($\cos\gamma_s$).

b: Minimum spacing between photovoltaic panels, designed to prevent shading on adjacent panels. This distance is dependent on the shading angle (χ_{min}) and an additional design angle (β).

7. Solar and Wind Combined

The integration of solar and wind energy into a unified renewable energy system can be implemented in various ways to enhance energy production, reliability, and efficiency [67]. Advanced control systems can optimize the performance of solar and wind installations. These controllers can redirect surplus power to charge batteries or meet immediate consumption demands, thereby balancing the load [68]. Solar panels and wind turbines can supply the electricity required for EVCSs. However, due to the intermittent nature of these energy sources, incorporating ESSs is essential. Battery storage devices ensure reliable EV charging, especially in regions with limited grid capacity [69]. Additionally, in areas without access to grid electricity, energy generated by solar panels and wind turbines can be stored in these batteries for later use.

8. Electric Vehicle Charging Stations (EVCSs)

EVCSs play a crucial role in providing affordable and clean electricity from the grid, while the growing adoption of renewable energy sources is accelerating the use of EVs [70]. Developing a robust network of charging stations will alleviate concerns among EV owners, enabling EVs to compete with ICE vehicles in terms of performance [71]. The tactical positioning of EVCSs and the influence of EVs on the distribution network have become significant areas of investigation in recent years [72]. A study [73] indicates that home charging stations are the most favored and crucial sites for recharging battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)

8.1. Charging Technology for EVs

This section describes the different levels, kinds, and schemes of EV charging, as well as the essential international standards to consider while developing an EVCS, as shown in Figure 2.

8.2. Charging Modes

EVCSs serve as refueling facilities that supply power to recharge EVs. Each charging point consists of a cable, a charging port, and an interface panel. The power outlet configuration depends on several factors, including voltage rating, frequency rating, and transmission standards, which vary based on the grid configuration. Organizations such as the Electric Power Research Institute (EPRI), the Society of Automotive Engineers (SAE), and the International Electrotechnical Commission (IEC) play significant roles in classifying charging modes and levels across different countries, ensuring consistency in safety standards. Established classifications include various charging types such as AC Level 1 (L_1), AC Level 2 (L_2), and direct current fast charging (DCFC) or level 3 (L_3) charging [74].

8.3. Level 1 (L_1) Charging

EVs are equipped with (L_1) charging cables, which are universally compatible and may be plugged into ordinary grounded 120-volt outlets. L_1 charging incurs expenses ranging from two to six dollars per mile and can replenish 40 miles over an eight-hour period. L_1 chargers are advantageous for companies and educational institutions, enabling EVs to charge during the day. L_1 charging is the most economical yet slowest option and can lower expenses when integrated with a tariff-based charging system.

8.4. Level 2 (L_2) Charging

L_2 charging stations are critical for EVs, providing a consistent power supply for charging. These stations need a single-phase 240-volt power supply with a maximum current capacity of 40 amps for residential and commercial applications and a three-phase AC power supply of 400 volts with a maximum current capacity of 80 amps for public stations. L_2 charge stations are commonly found in public and residential locations, and they provide fast and efficient vehicle charging [75].

8.5. Level 3 (L_3) Charging

EVs can be charged at L_3 charging stations, predominantly located in public and commercial spaces. These stations provide a comparable user experience to conventional filling stations, featuring charging voltages between 200 and 600 volts and power outputs from 36 to 240 kW. DC charging technology transforms AC power from an external charger, with DC L_1 charging stations delivering a power output of 36 kW and a current capacity of 80 amps. Nonetheless, DC fast charging stations incur substantial installation expenses [76]. L_3 chargers, also known as rapid DC chargers, are ideal for highway use, as they can charge an EV's battery to 80% capacity within 20 to 30 min. Fast charging on highways plays a crucial role in facilitating long-distance travel [69].

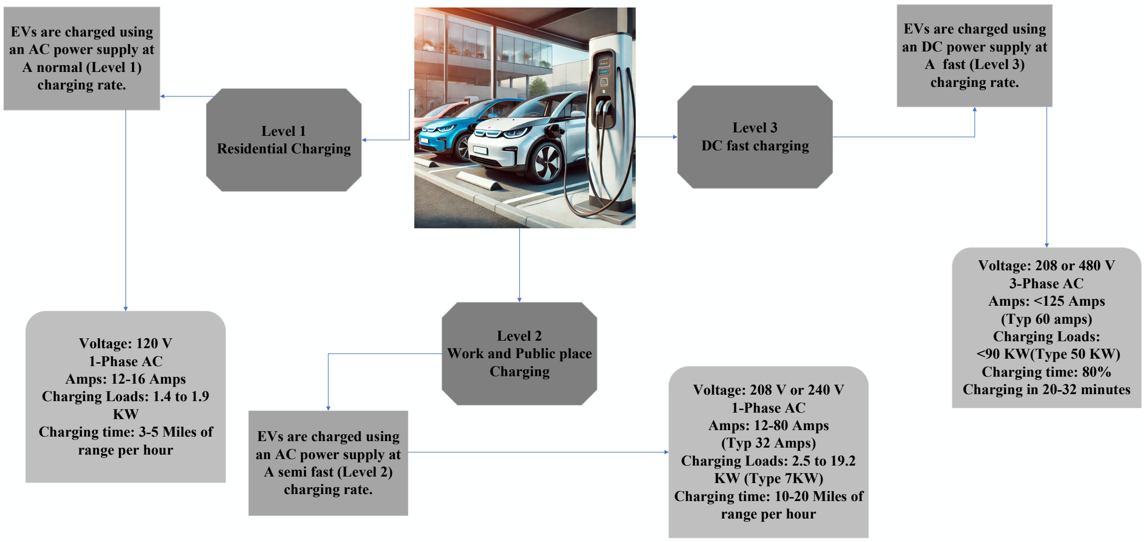

Figure 2. EV Charging Infrastructure [76].

8.6. Charging Infrastructure Sizing Criteria and Load Assumptions

The charging infrastructure and load modeling assumptions were selected to ensure technical realism and economic consistency with the highway case study context. A 50 kW Level 3 DC fast charger was adopted as it represents a practical balance between charging speed and infrastructure cost for intercity corridors, where reduced dwell time is required but ultra-fast systems (150–350 kW) would impose significantly higher capital and grid reinforcement costs. The deployment of two chargers reflects a pilot-scale implementation along the 22 km corridor, consistent with moderate EV penetration in early adoption stages while limiting initial investment risk. The operational window of 9:00–14:00 (5 h per day) was intentionally aligned with peak solar irradiance to maximize photovoltaic utilization and avoid overestimation of demand during early market development. The 35% DC primary load share is not an imposed assumption but an optimization-derived outcome under the $0.1/kWh scenario, representing the proportional contribution of EV fast charging within the hybrid energy balance. Although lithium-ion batteries dominate current markets (2025), lead-acid storage was selected to provide a conservative economic baseline within the HOMER Pro modeling framework, focusing on feasibility demonstration rather than storage technology comparison.

9. Case Study Analysis

We analyze the 22-km Tabriz-Sahand route and use the HOMER program to evaluate various scenarios for establishing an EVCS. The HOMER program assesses multiple energy resources to determine the most effective power transmission options for electrifying the station. According to the Köppen-Geiger climate classification map, the Tabriz-Sahand highway falls within a cold semi-arid climate zone (BSk) [77]. This region experiences dry, hot summers and cold winters with minimal precipitation. Summer temperatures can reach up to 30 degrees Celsius, while winter temperatures often drop below freezing, accompanied by snowfall.

The climatic conditions of this location can substantially influence EVCSs, as low temperatures in winter adversely affect the functioning of equipment and batteries. Moreover, during summer, the clear weather offers numerous benefits for solar panel utilization; yet, dust accumulation could reduce their performance in the warmer months. In addition to solar panels, wind turbines may be employed based on geographical conditions and favorable wind currents, particularly during months with reduced sunlight.

The utilization of diverse energy sources enhances sustainability and energy efficiency, making it appropriate for fulfilling the electrical requirements of this region. Furthermore, batteries and grid energy can enhance reliability.

Figure 3 illustrates the utilization of Enlil wind turbines, LONGi Solar LR6-60PB solar panels, and grid electricity. To improve the system's reliability, we utilized a Generic 1kWh Lead Acid battery and a Leonics MTP-413F 25kW inverter in this simulation.

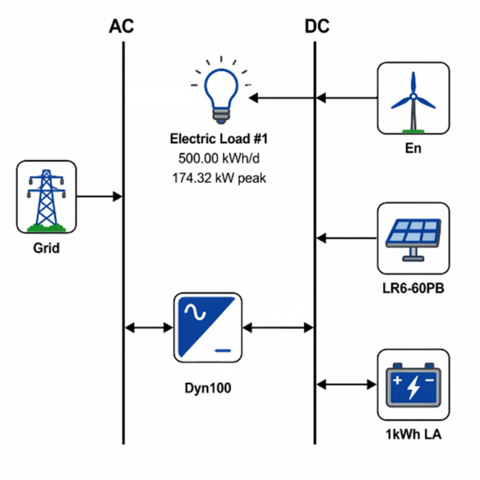

Figure 3. Integrated Wind-Solar Hybrid System with Battery Storage and Grid Connection.

This simulation analyzed an EVCS equipped with two fast-charging nozzles, each delivering 50 kilowatts of power. The charging period is set for 5 h daily, from 9 AM to 2 PM. Figures 4 and 5 illustrate the wind speed and solar radiation intensity in this region.

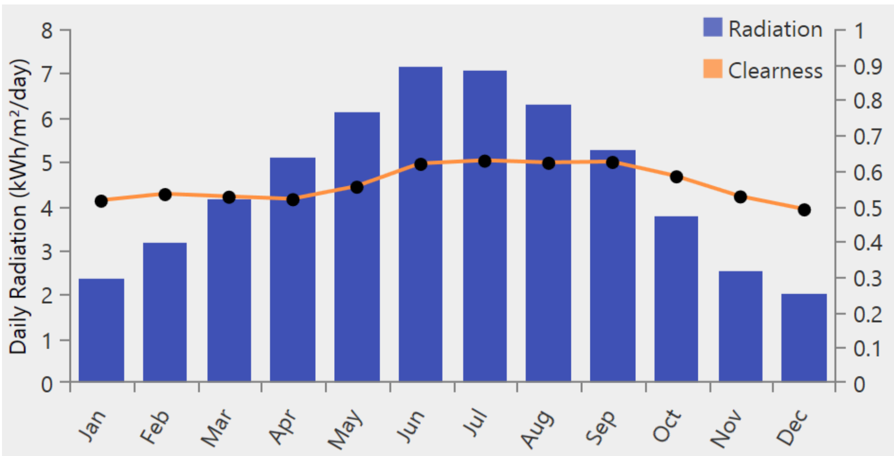

Figure 4. The range in radiation intensity over the months of the year.

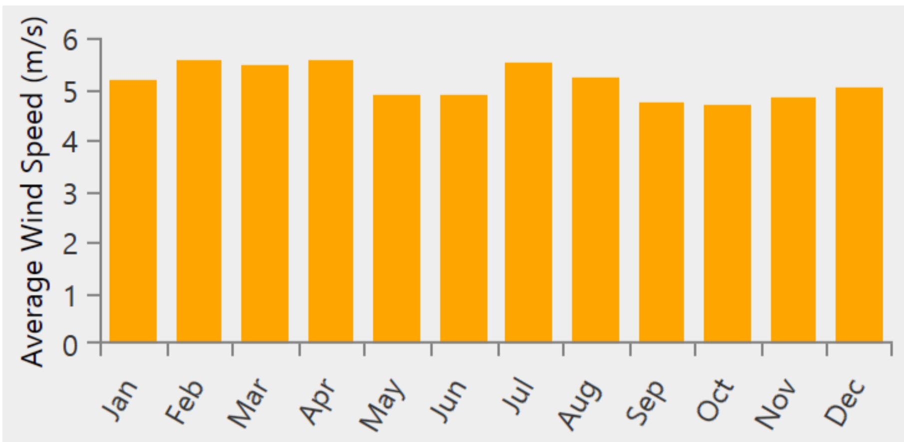

Figure 5. Average wind speed over 12 months of the year.

The HOMER program analyzed various scenarios to assess the economic viability of the proposed strategy, running a total of 74,895 simulations. The results, illustrated in Table 2, indicate that due to the low electricity cost in Iran ($0.002 per kWh in 2024), the most economical option is to rely solely on grid electricity. In contrast, the most expensive alternative involves implementing a hybrid system that integrates multiple energy sources.

Table 2. Multiple scenarios are evaluated in the software with or without resource availability.

Optimization Results														
				LR6-60PB Solar Panel (kWh/yr)	**Enlil Wind Turbine (kWh/yr)**	**1kWh LA Battery (kWh)**	**Grid (kWh/yr)**	**Renewable penetration (%)**	**Capex ($)**	**Replacement (M$)**	**O&M (M$)**	**Salvage (M$)**	**Total ($)**
✓	✓	✓	✓	3337	19,656	0.6	181,733	8.1%	163,203	1.723	1.322	−2.539	669,091
-	✓	✓	✓	-	19,656	1.2	183,860	6.5%	161,996	1.713	1.310	−2.520	665,656
✓	✓	-	✓	3688	19,656	-	181,506	8.3%	161,791	1.709	1.311	−2.521	661,796
-	✓	-	✓	-	19,656	-	183,860	6.5%	161,567	1.712	1.309	−2.523	659,632
-	-	✓	✓	-	-	1.2	189,086	0%	160,256	1.727	1.306	−2.540	653,334
✓	-	✓	✓	356	-	0.6	188,859	0.2%	160,096	1.726	1.306	−2.542	650,653
✓	-	-	✓	575	-	-	188,719	0.3%	159,732	1.724	1.304	−2.541	647,172
-	-	-	✓	-	-	-	189,086	0%	159,554	1.723	1.302	−2.539	646,306

Table 2 presents the optimization results for various system configurations in a hybrid energy system. It displays key metrics, such as system architecture, the produced energy, capital costs, replacement costs, operation & maintenance costs, salvage costs, and total costs. The data highlights how varying system components (e.g., PV capacity, grid dependency) impact economic and operational performance, estimated at $669,091. In contrast, relying solely on grid electricity would cost $646,306. Additionally, the figure presents several alternative scenarios with varying costs. Figures 6 and 7 illustrate grid-dependent and hybrid cash flow in the project lifetime (20 years). Negative costs in salvage indicate total income or saving money (which can include selling equipment or income after the project ends).

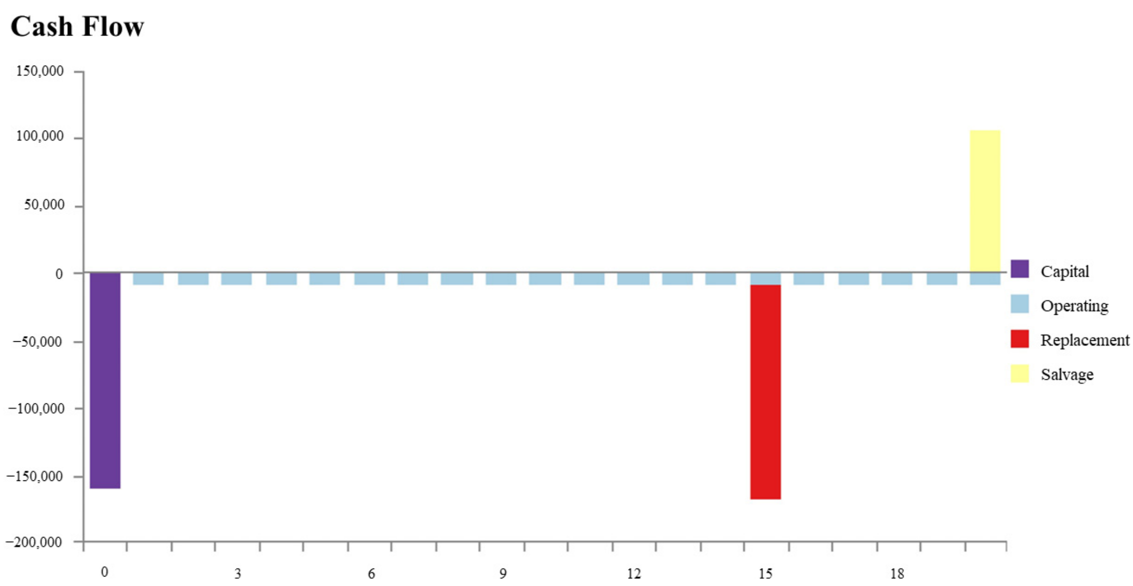

Figure 6. Nominal cash flow diagram for economical scenario.

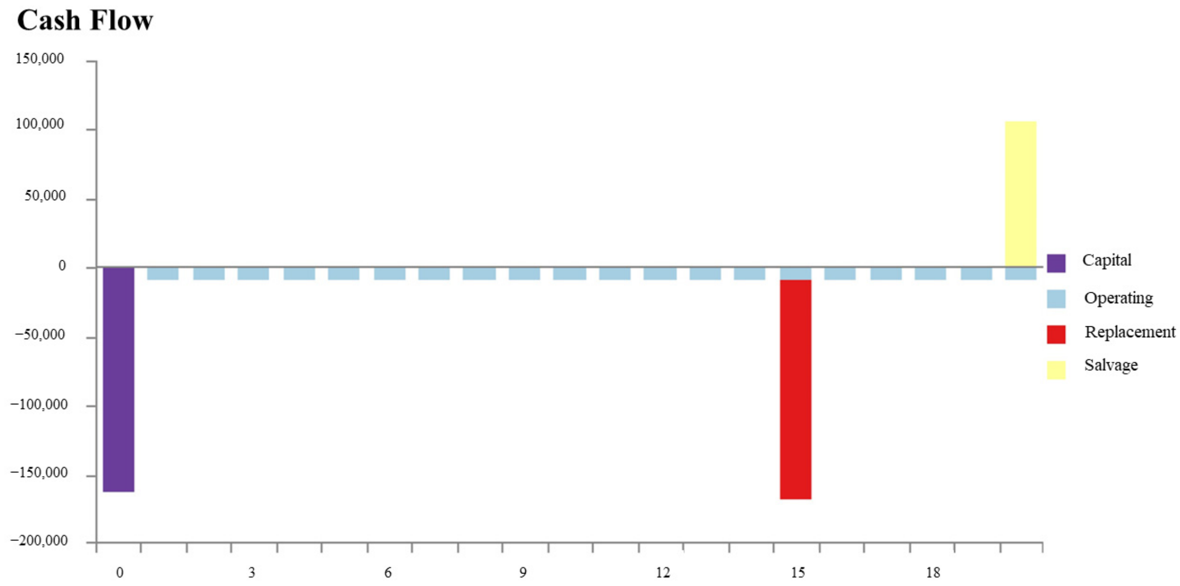

Figure 7. Nominal cash flow diagram for hybrid scenario.

Figures 8 and 9 illustrate monthly electrical energy production in grid-dependent and hybrid scenarios, with an annual consumption of 189,086 and 181,737 kilowatt-hours.

Analyzing the prevailing electricity prices in Iran and contrasting the scenarios of relying solely on grid electricity with a hybrid approach reveals that the investment and overall costs of the grid-dependent system are more economically advantageous than those of the hybrid systems, despite the latter incorporating only about 8% of renewable energy and exhibiting a cost disparity of approximately $22,785.

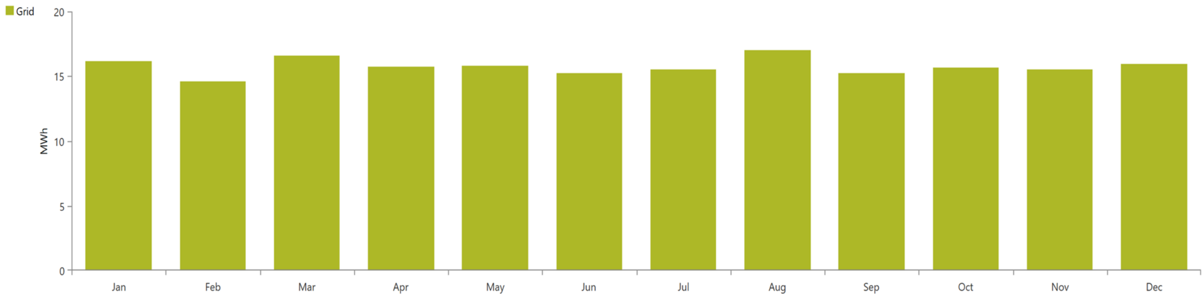

Figure 8. The amount of electrical energy generated by the grid across different months of the year in an economic scenario.

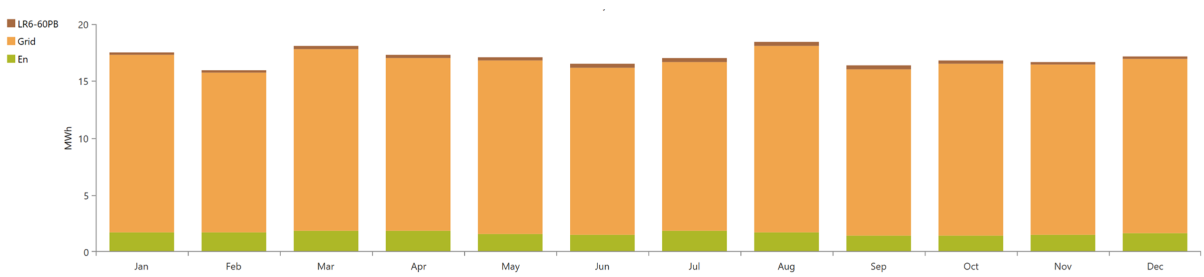

Figure 9. The amount of electrical energy generated by the grid across different months of the year in a hybrid scenario.

10. Distinction between Long-Term Techno-Economic Optimization and Dynamic Control Strategies

System configuration—including photovoltaic capacity, vehicle-induced wind turbine integration, battery storage sizing, and grid interaction—is determined through lifecycle cost minimization over a 20-year project horizon using HOMER Pro. The objective function minimizes NPC subject to technical constraints such as SOC limits, inverter capacity, grid purchase restrictions, and load requirements. Operational behavior is simulated using rule-based dispatch strategies (load-following and cycle-charging), which allocate power resources at an hourly resolution (8760 time steps per year) based on economic priority rather than state-space feedback regulation. Accordingly, the performance metrics evaluated in this work—NPC, LCOE, renewable penetration ratio, emission reductions (CO_2, SO_2, NO_x), and long-term energy balance—are system-level economic and environmental indicators. They do not represent transient dynamic control indices such as voltage regulation quality, frequency stability, or closed-loop state tracking performance. Additionally, a comprehensive electricity price sensitivity analysis ($0.002–$0.5/kWh) is conducted to assess robustness under market uncertainty. The results demonstrate a clear economic transition threshold and renewable penetration increase from 0% to approximately 96%, alongside substantial emission reductions and long-term cost improvements under higher tariff conditions.

11. Sensitivity Analysis for Electric Price

Sensitivity analysis is critical for understanding the impact of varying electricity prices on the economic and technical performance of hybrid energy systems. This section evaluates the influence of electricity price variations on the system's NPC, LCOE, and other economic indicators, as simulated using HOMER Pro (version 3.18.3). The sensitivity analysis was conducted by varying the electricity price in a range of values while keeping other parameters constant. HOMER Pro's optimization results and cost breakdown data were used to analyze the changes in NPC, LCOE, and operating costs. The electricity price was varied between $0.002/kWh and $0.5/kWh to reflect realistic market conditions. As electricity prices increase, the system's economic performance improves, primarily due to increased revenue from energy sales. This trend highlights the importance of electricity prices in determining the feasibility of hybrid energy systems. Higher electricity prices incentivize greater reliance on renewable energy sources, reducing dependence on grid power. The findings show that as electricity prices rise, renewable energy becomes more cost-effective. If the electricity selling price reaches $0.01 or $0.1 per kilowatt-hour, the use of renewable energy in electricity generation rises to 57.3% and 96%, respectively, under the most cost-effective scenarios. Figure 10 shows a surface plot of the system's sensitivity analysis for different electricity prices, renewable penetration, and the project's cost, and Figure 11 depicts the costs for each scenario based on various electricity prices. As shown in this figure, rising electricity prices increase project costs and the use of renewable energy. With an increase in electricity prices of $0.05, renewable energy penetration exceeds 90%.

As energy prices in Iran have significantly increased in recent years, electricity costs are expected to rise further in the coming years. As a result, in the next simulation, we assumed the price of electricity to be $0.1.

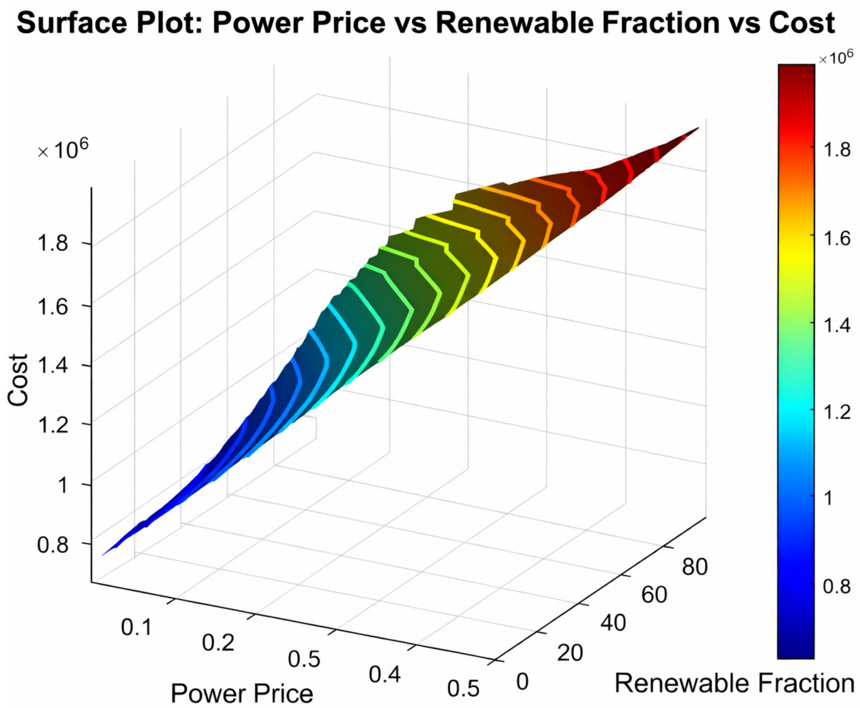

Figure 10. Results of Sensitivity Analysis in different electricity prices (0.002 to 0.5 dollars).

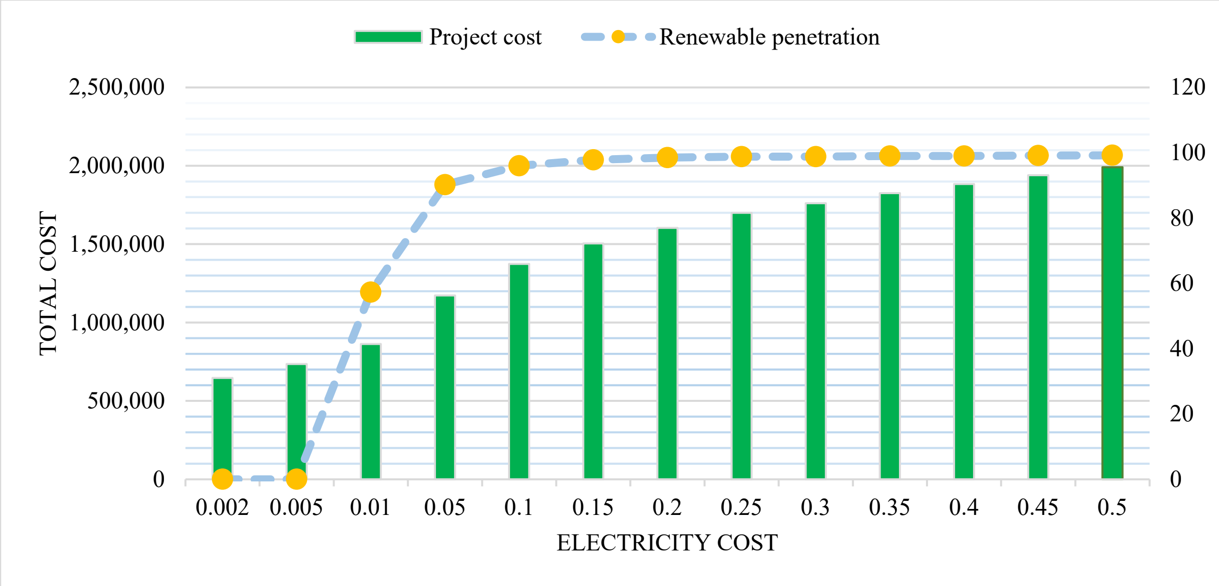

Figure 11. Project cost chart based on different electricity prices and the impact of renewable energy penetration based on each energy price in the project's lifetime (20 years).

If we consider that the trend of rising electricity prices in Iran eventually reaches the price of electricity in Germany, which is nearly $0.126 per kilowatt-hour, the simulation results are presented in Table 3.

Table 3. Multiple scenarios are evaluated in the software with or without resource availability.

Optimization Results														
				**LR6-60PB Solar Panel (kWh/yr)**	**Enlil Wind Turbine (kWh/yr)**	**1kWh LA Battery (kWh)**	**Grid (kWh/yr)**	**Renewable Penetration (%)**	**Capex ($)**	**Replacement (M$)**	**O&M (M$)**	**Salvage (M$)**	**Total (M$)**
✓	✓	-	✓	367,640	157,247	-	20,913	96%	212,106	1.505	2.107	−2.450	1.373
✓	✓	✓	✓	375,273	157,247	0.6	20,425	96.1%	213,632	1.509	2.114	−2.459	1.378
✓	-	-	✓	481,958	-	-	24,007	94.9%	207,273	1.548	2.239	−2.587	1.407
✓	-	-	✓	462,691	-	0.6	25,137	94.6%	206,729	1.568	2.241	−2.602	1.414
-	✓	-	✓	-	707,611	-	62,966	90.9%	253,222	1.568	2.675	−2.311	2.185
-	✓	✓	✓	-	687,955	0.6	64,154	90.5%	251,093	1.575	2.683	−2.320	2.190
-	-	-	✓	-	-	-	189,086	0%	159,656	1.724	4.192	−2.540	3.535
-	-	✓	✓	-	-	2.4	189,086	0%	160,856	1.730	4.198	−2.540	3.549

As shown in Table 3, the most cost-effective and optimal scenario is hybrid electricity generation from wind and solar energy combined with the grid, with a total cost of 1.373 million dollars over a 20-year period with an electrical permeability of 96 percent. In contrast, if we only relied on the grid for electricity, our total cost would be 3.549 million dollars, with an electrical permeability of 0 percent. The prices of capital, operating, replacement, and salvage are shown in Figures 12 and 13.

Figure 14 and Table 4 illustrate the monthly electric production and energy balance for a hybrid energy system as part of a sensitivity analysis. It provides a breakdown of energy production and consumption, as well as the contributions of various energy sources. If the price of electricity is 0.1 dollars per kilowatt-hour, Enlil VAWT (wind turbines) contributes the largest share (28.8%) of annual energy production. LONGI Solar LR6-60PBE accounts for 67.4% of the total production. Grid purchases make up a minimal contribution (3.83%). DC primary load constitutes 35% of the total annual energy consumption. The system achieves a high renewable penetration of 96%. Maximum renewable penetration is 176%, indicating substantial energy independence and surplus. The bar graph shows the monthly distribution of electricity production, with contributions from solar (brown), wind (green), and grid (orange) sources. Solar and wind energy production remains consistent throughout the year, meeting and exceeding load requirements.

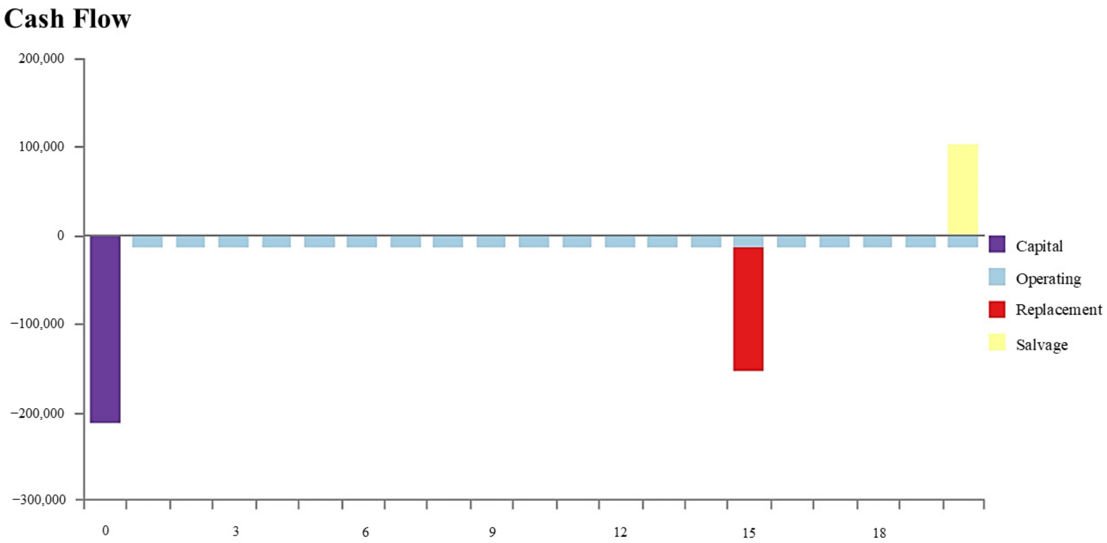

Figure 12. Nominal cash flow of the project considering capital, operating, replacement, and salvage.

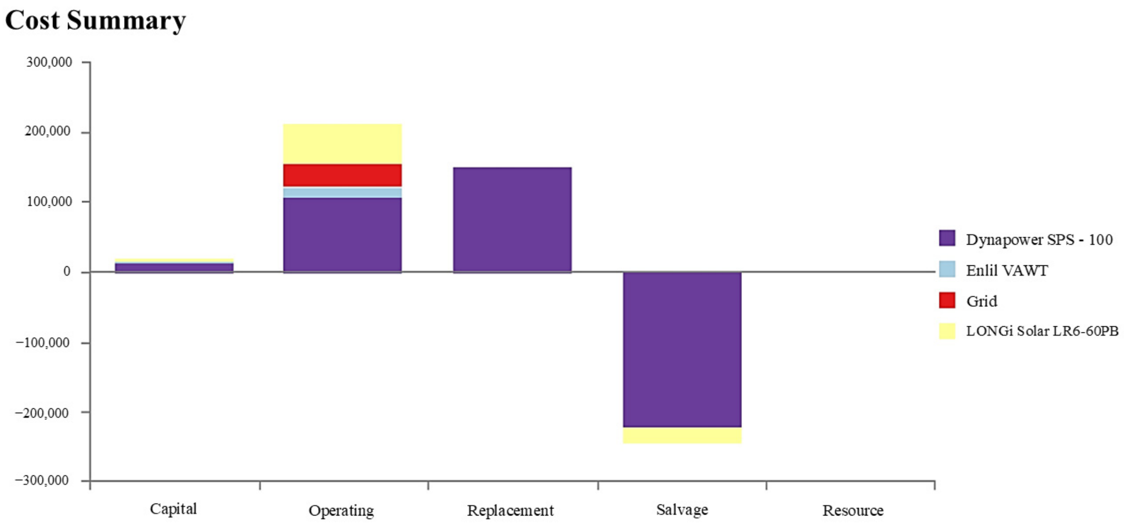

Figure 13. The project's cost summary takes into account the wind turbine, solar panel, grid, and inverter.

Table 4. Renewable energy contribution in a hybrid energy system.

Production	KWh/yr	%	Consumption	KWh/yr	%	Quantity	KWh/yr	%
LONGI Solar LR6-60PB	367640	67.4	AC Primary Load	0	0	Exess Electricity	11,592	2.12
Enlil VAWT	157247	28.8	DC Primary Load	182,500	35	Unmet	0	0
Grid Purchases	20913	3.38	Deferrable Load	0	0	Capacity	176	0.0966
Total	545799	100	Grid Sales	338,692	65	Renewable Fraction		96
			Total	521,192	100	Max, Renew, Penetration		176

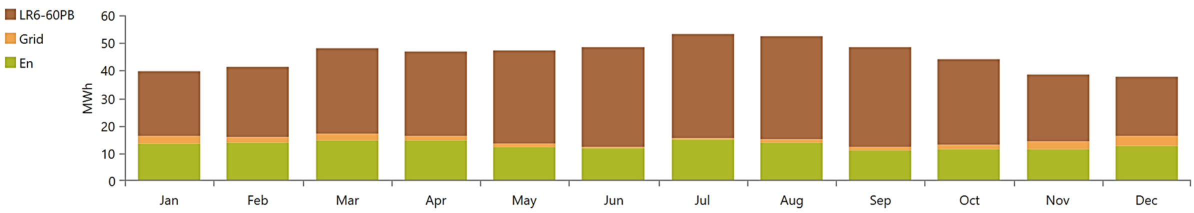

Figure 14. Monthly electric production and renewable energy contribution in a hybrid energy system (with an electricity price of 0.1 dollars).

12. Emission

The use of renewable energy instead of fossil fuels has a significant impact on lowering air pollution. As shown in Figure 15, increased use of renewable energy to power EVCSs on highways reduces emissions of three well-known pollutants: CO_2, SO_2, and NO_x. (Negative values on the chart indicate that we can prevent the emission of that amount of pollutant gas.) For example, if we generate all of our electricity from the grid and do not use any renewable energy sources, we will produce 120,000 kg of CO_2, 518 kg of sulfur dioxide, and 253 kg of nitrogen monoxide and its derivatives each year. The amount of pollutants produced decreases as renewable energies become more widely used.

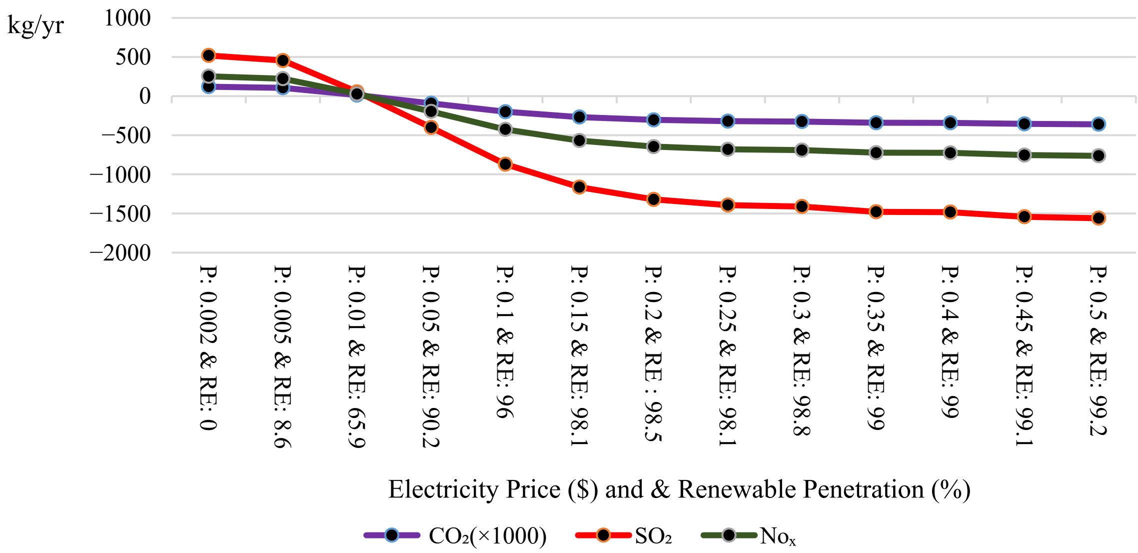

Figure 15. Chart of the emission of the three main air pollutants (CO_2, SO_2, NO_x) based on changes in electricity sales prices and the level of renewable energy participation.

13. SWOT Analysis of Hybrid Renewable Energy for EVCS in Highways

The development of EVCSs along highways through solar and wind energy has advantages and disadvantages. Its benefits are fewer greenhouse gas emissions and reduced dependence on fossil fuels. It also opens the potential for clean energy distribution where there is limited electrical grid infrastructure. Other advantages of the approach are minimized maintenance and operation expenses compared to earlier methods, resulting in lower long-term costs of operation. Its high scalability and modularity enable the system to be expanded to cope with growing demand. In addition, it is capable of supplying highway lights as well as EVs. Besides these benefits are some drawbacks such as high initial costs and a lack of ability to sustain the generation of power since it relies on the weather. There is enormous space required to position wind turbines, and the panels are inconvenient in some places. The challenge of retaining some technology is required, which incurs higher costs. There are so many opportunities for the development of this technology. Governments, for example, can assist such a strategy by offering subsidies, tax reliefs, and financial facilities. As a result of the exponential growth of the EV sector, it is imperative that sustainable charging networks be put in place, and investors should invest in such a strategy. Increased technologies for energy storage mean electricity can be stored in peak load situations and reduce the uncertainty of the production process. Two changes that are expected to potentially raise charging station output are smart energy management and smart grids. Such an initiative, however, could be subject to legal obstacles and changing policies related to energy. Other problems include competition in the market from grid-connected and fossil fuel-based charging stations, which could lower the adoption rate of the plan. Unpredictable patterns of wind and solar radiation also have the potential to disrupt renewable energy supply. Interconnection with the internet presents cybersecurity issues in smart systems, and utilization of certain lands for building the system could be the cause of concerns from environmental groups. The mentioned items are summarized in Figure 16.

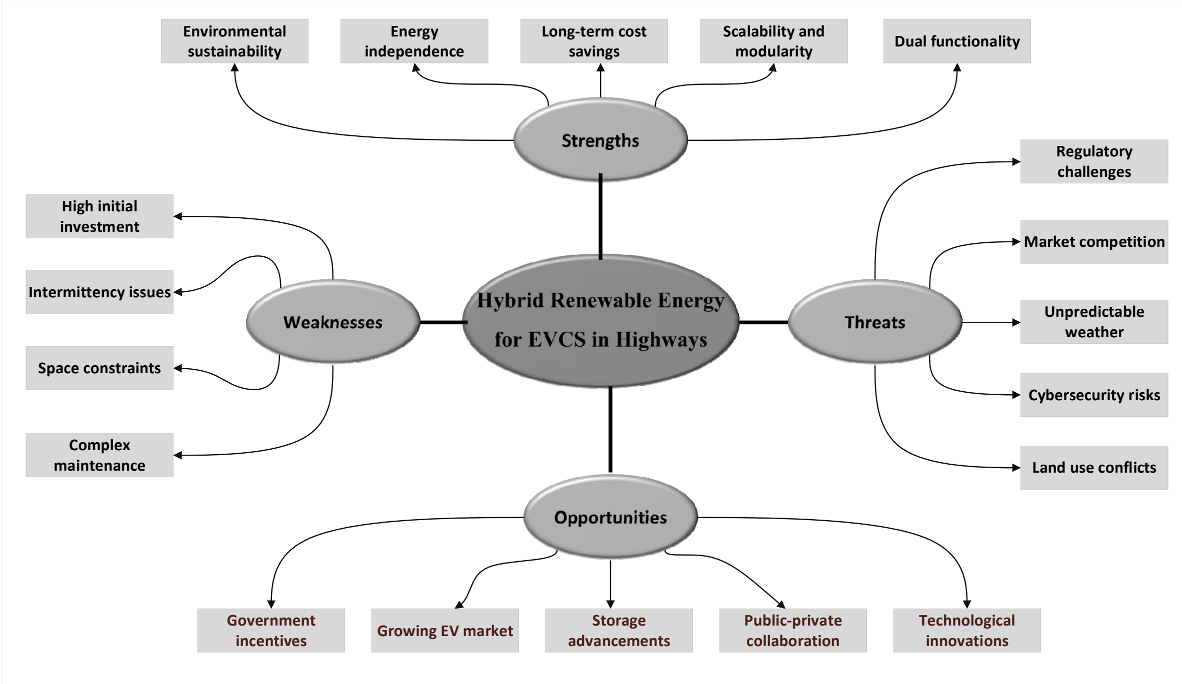

Figure 16. SWOT analysis of hybrid renewable energy systems for EVCSs on highways, highlighting strengths, weaknesses, opportunities, and threats of this sustainable technology.

13.1. Uncertainty and Stochastic Considerations

The renewable resource inputs are derived from multi-year averaged meteorological datasets for the Tabriz–Sahand region, ensuring that the modeled profiles are representative rather than based on a single atypical year. Furthermore, the simulations were conducted with an hourly temporal resolution (8760 time steps per year), allowing the model to capture both daily and seasonal variability in solar radiation, wind speed, and EV charging demand. In addition to resource variability, economic uncertainty is addressed through a structured electricity price sensitivity analysis covering a wide range ($0.002–$0.5/kWh), which functions as a proxy for market and policy uncertainty in subsidized and deregulated electricity environments. While a fully stochastic framework—such as Monte Carlo-based probabilistic modeling of wind, solar, and demand uncertainties—would provide deeper statistical insight, it falls beyond the scope of the present techno-economic planning study and is therefore proposed as a direction for future research.

13.2. Comparative LCOE Assessment and Electricity Price Breakeven Analysis

The results indicate that under highly subsidized electricity prices ($0.002/kWh), the grid-only scenario yields a lower LCOE and total NPC. However, as electricity prices increase, the hybrid configuration becomes progressively more competitive. A breakeven electricity price is identified within the approximate range of $0.01–$0.05/kWh, beyond which the economic advantage shifts significantly toward renewable integration. Notably, when the electricity price reaches $0.05/kWh, renewable penetration exceeds 90%, and the hybrid system demonstrates clear long-term economic superiority. This analysis quantitatively establishes the economic transition threshold at which hybrid renewable-based EV charging infrastructure becomes financially preferable to grid-dependent operation, thereby strengthening the policy and investment relevance of the study.

13.3. Policy Implications

The findings of this study have important policy implications, particularly for countries operating under subsidized electricity markets such as Iran. When electricity tariffs are artificially low (e.g., $0.002/kWh), grid-dependent EV charging infrastructure appears economically optimal in the short term. However, such pricing structures mask the true cost of generation, distort investment signals, discourage private-sector participation in renewable energy projects, and increase long-term fiscal pressure on governments due to subsidy burdens. As demonstrated by the sensitivity analysis, once electricity prices approach more cost-reflective levels (approximately $0.01–$0.05/kWh), hybrid renewable configurations rapidly become economically competitive, and at \$0.05/kWh renewable penetration exceeds 90%. This identifies a clear economic transition threshold that policymakers must anticipate.

Gradual subsidy reform therefore represents both a risk and an opportunity. In the absence of proactive planning, rising electricity tariffs could sharply increase EV charging costs, potentially slowing EV adoption and undermining transport decarbonization goals. Conversely, if tariff reforms are accompanied by targeted renewable energy incentives—such as capital subsidies for PV and wind installations, tax credits, low-interest green financing, feed-in mechanisms, or accelerated depreciation schemes—the transition can stimulate investment in hybrid EV charging infrastructure while mitigating consumer price shocks.

From a climate policy perspective, the emission analysis confirms that increasing renewable penetration significantly reduces CO_2, SO_2, and NOx emissions. Under high-renewable scenarios (≈96% penetration), annual avoided emissions are substantial compared to grid-only operation. These reductions align directly with national commitments under international climate frameworks and long-term net-zero strategies. Therefore, integrating renewable-based EV charging infrastructure along highways can serve as a dual-sector decarbonization mechanism, simultaneously addressing transport electrification and power-sector emissions. Furthermore, highway-based hybrid EV charging stations can enhance energy security by reducing peak grid stress, especially during daytime high-demand periods. Distributed renewable integration lowers transmission losses, mitigates congestion in regional grids, and improves resilience in corridors with limited grid capacity. For policymakers, this supports strategic infrastructure planning where renewable-powered EV charging hubs are prioritized in intercity transportation networks.

Additionally, the breakeven electricity price identified in this study provides a quantitative decision-support metric. Governments can use this threshold to design phased tariff adjustments while simultaneously deploying renewable support mechanisms to maintain charging affordability.

13.4. Integrated Techno-Economic Optimization and Sensitivity-Based Evaluation Framework

First, the core framework is based on long-term techno-economic optimization, where system sizing (PV capacity, wind turbine integration, battery storage, and grid interaction) is determined by minimizing the NPC over a 20-year project lifetime. This optimization is implemented using HOMER Pro, which performs lifecycle cost minimization subject to technical and operational constraints. The objective function incorporates capital costs, replacement costs, operation and maintenance costs, fuel/grid purchase costs, and salvage value, ensuring that system configuration decisions are economically grounded and reproducible.

Second, the operational layer of the model relies on rule-based dispatch modeling rather than state-space dynamic control. Specifically, predefined dispatch strategies (e.g., load-following or cycle-charging) govern how renewable generation, battery storage, and grid resources interact at each hourly time step (8760 h per year). Battery SOC limits, inverter constraints, and grid capacity limits are explicitly imposed to ensure technical feasibility. This structure clarifies that the study does not implement predictive control algorithms (such as MPC), but instead evaluates system performance under realistic operational rules commonly used in microgrid feasibility analysis.

Third, the study incorporates sensitivity-driven scenario evaluation as a structured uncertainty analysis tool. Instead of relying on a single economic assumption, electricity price is varied across a broad range (\$0.002–\$0.5/kWh), reflecting both subsidized and market-based pricing environments. This parametric variation enables identification of transition thresholds, breakeven electricity prices, and renewable penetration inflection points. The sensitivity framework ensures that conclusions are not dependent on a single deterministic economic condition, thereby strengthening robustness and transparency.

Fourth, emission quantification is integrated as a post-optimization environmental assessment layer. Based on grid energy consumption levels determined by each scenario, associated CO_2, SO_2, and NOx emissions are calculated using standardized emission factors. This enables a coupled economic–environmental evaluation, linking renewable penetration directly to measurable pollutant reduction outcomes. Importantly, emissions are not assumed but are derived from scenario-specific energy balances, ensuring internal methodological consistency.

14. Conclusions

Integrating wind turbines and solar panels along highways can reduce CO_2 emissions, provide illumination, and power EVCSs, particularly in regions without access to the power grid or where the grid cannot adequately supply energy to the roadway. Additionally, the effective use of these facilities makes the construction of EVCSs adjacent to highways more feasible. Combining these two energy sources with a battery storage system can ensure a sustainable energy supply for EVs on highways. We must optimize site selection and design to ensure economic viability and efficiency. Research from this study recommends placing helical wind turbines along highways and identifies Type 3 chargers as the optimal choice for enhancing and expediting charging services. This paper evaluates the feasibility of constructing an EVCS on a highway in Tabriz, Iran, using solar and wind energy in combination with grid electricity and storage capabilities. We used HOMER software for simulation, which generated various scenarios. The scenario, including all renewable energy sources (with a renewable penetration of 8.1%) along with grid electricity, estimated a capital cost of $163,203 and a total cost of $669,091 with a project lifespan of 20 years. In contrast, the scenario relying solely on grid electricity reached a capital cost of $159,554 and a total cost of $646,306. This cost difference is primarily due to the low electricity price in Iran, which is $0.002 per kilowatt-hour. With the increase in electricity prices in Iran, it is not unexpected that the price of electricity in the near future may reach European levels. However, in countries with high electricity costs or limited grid access, the use of renewable energy sources can offer significant benefits. There was a price sensitivity analysis and an analysis of electricity prices up to $0.5. For example, if the price of electricity in Germany is $0.1, it would make sense to use a hybrid system to build an EVCS with a capital cost of $212,106 and a total cost of $1.373 million, with a high contribution from all the renewable energies mentioned (96%). Additionally, the use of renewable energy at EVCSs on highways offers benefits such as reducing pollutant emissions, promoting environmental sustainability, and increasing energy independence. However, it requires a high initial investment, which can be supported by government backing and appropriate policy-making to help develop this sector.

Author Contributions

A.B.: Conceptualization, Methodology, Software, Writing—original draft. M.M.H.: Project management, Visualization, Writing—original draft and Literature review, Editing. M.H.N.: Resources, Investigation, Writing—original draft, Software, Editing. M.A.: Supervision, Methodology, Writing, review, Editing. M.N.-H.: Supervision, Methodology, visualization, Final editing. K.Z.: Supervision, Methodology, Visualization, Final editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT and Quillbot to paraphrase the text, improve fluency, and correct grammatical errors. No text was generated by AI from scratch. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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