Energy Equip. Sys./ Vol. 13/No. 4/December 2025/ 415-429

Energy Equipment and Systems

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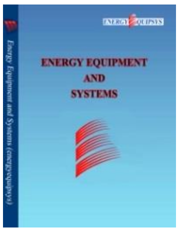

Decarbonizing transport: Energy, economic and environmental insights from EV charging stations

Manuscript Type
Research Paper

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Article history:

Received: 6 March 2025
Revised: 16 May 2025
Accepted : 13 July 2025

ABSTRACT

Expanding electric vehicle (EV) charging stations (CSs) is a key strategy to promote EV adoption over gasoline vehicles. Due to the lack of local feasibility studies in Iran, this work presents a sensitivity analysis and a techno-economic-environmental (3E) assessment of a wind-solar-powered charging station in Shahrekord, Iran. Simulations were conducted in HOMER, with the system connected to the national power grid. The optimal configuration includes a 50 kW solar system, a 25 kW wind turbine, and a 40 kW converter, achieving a levelized cost of electricity (LCOE) of 0.058 $/kWh. Solar panels and wind turbines annually generate 80,094 kWh (41%) and 51,420 kWh (26%), respectively, with 42,896 kWh sold to the grid. CO_2 emissions amount to 13,369 kg/year in the optimal scenario. Sensitivity analysis shows that higher wind speeds and solar irradiance lead to negative LCOE and pollutant generation rates. This study offers essential insights for optimizing renewable energy-based EV charging stations in Iran and contributes to global efforts to reduce CO_2 emissions and improve energy efficiency in transportation.

Keywords: EV; Charging Station; 3E Analysis; HOMER; Cost of Electricity.

1. Introduction

Leveraging electricity generated from renewable energy sources (RESs) plays a pivotal role in reducing costs, time, and the rate of environmental pollution, which are three leading factors to consider in today's communities [1-3]. Nearly 27.3% of global power generation is from RESs, which reached the rate of 2588 GW at the end of 2019 [4]. Of these energy resources, a global portion of using wind and solar energies for power generation has been remarkably increased [5-11]. RESs with EVs indicate an excellent potential to resolve economic and environmental problems [12]. EVs enhance energy productivity, as they no longer need direct fuel combustion and rely on electricity [13, 14]. The idea of using EVs has rapidly gained elevated attention in the recent decade so that in 2018, the number of EVs was reached 5 million,

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with a 63% increase as compared with the previous year (i.e., in 2017) [15]. The UK government proclaimed that the sale of all fossil fuel vehicles will be banned by 2024 [16]. Furthermore, the French government has announced its intention to cease greenhouse gas emissions from automobiles by the year 2040 [17]. Figure 1 shows the prediction of selling EVs by 2030 in countries that have been regarded as the largest global markets. It is prophesied that the infrastructures of CSs to be advanced with an increase in the number of EVs, which consequently raises the demand for electricity [14]. Additionally, concerns regarding the standard of electrical power, encompass aspects like grid connectivity, assimilation with recently incorporated nonlinear loads, and the operation of high-frequency switching converters [18, 19] have lifted up the demand for various types of RES-based EV CSs in many countries [13]. Fig. 2 gives a schematic representation of a hybrid solar-wind charging system.

2. Literature Review

Table 1 summarizes the recent work done on electric vehicle CSs.

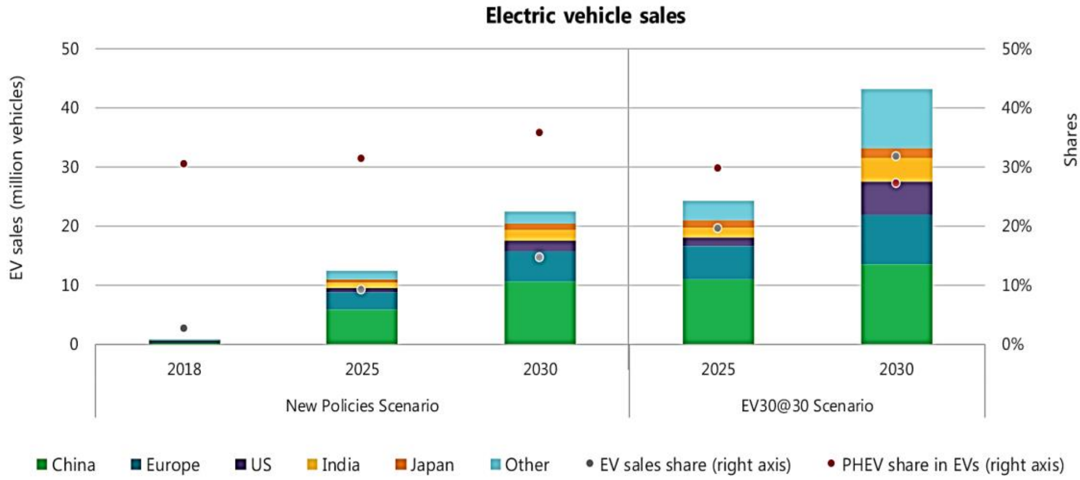


Fig. 1. Projection of EV Sales by the International Energy Agency (2018-2030) [20]

Fig. 2. Hybrid charging system [21]

Table 1. Summary literature review

Ref.	Objective	Software or analytic approach utilized	Results
[22]	A new approach for the optimal assignment and determination of the rate of RESs and EV charging simultaneously, as well as the management of the process of charging EVs in smart grids	Weighting coefficients method and improved Genetic Algorithm-Particle Swarm Optimization (GA-PSO) in MATLAB	The results show the efficiency of this approach in achieving pre-defined goals and a shorter duration for finding an optimal solution than the former approaches
[23]	A new two-step method for finding the optimal location of EV and RES parking considering economic and technical restrictions	GA and PSO algorithms	Using this method and the simultaneous presence of EV and RES in the grid will diminish costs and improve the performance of the grid
[24]	Dynamic randomized pricing of EV CSs through integrating RESs and energy saving	Stochastic Dynamic Programming Algorithm vs. Greedy Algorithm (Benchmark Algorithm)	Utilizing the SDP algorithm can yield a profit that is 7% higher compared to employing the greedy algorithm.
[25]	The analysis of integrated RE systems and smart grids to optimize quality of voltage and lessen losses of harmonic distortion in EV CSs	MATLAB/Simulink	The suggested model can efficiently manage the electrical energy of the grid by using batteries at the peak power consumption and recharging them at non-peak power consumption, as well as diminishing load in a converter and the duration of EV charging
[26]	An optimal designing approach using a new GIS for high-density RES-based EV CSs	TRNSYS software and GIS software	The suggested method aims to reduce the lifetime price of CSs
[27]	Designing a grid-connected EV CS energized by wind and solar energy	MPPTM technique	The fabricated CS supplies electricity for EVs and contributes to the local grid of the urban electricity distribution
[28]	Design and optimization of a solar-wind hybrid EV charging station using HOMER software to meet the increasing electricity demand for EVs while reducing reliance on conventional energy resources.	HOMER software	The optimal hybrid system solution was 44.4% wind energy and 55.6% solar energy, producing 843,150 kWh annually at a cost of $0.064/kWh, demonstrating the feasibility and cost-effectiveness of the system for sustainable EV charging.
[29]	Design an efficient Hybrid RES framework that integrates photovoltaic (PV) and wind energy for EV charging, ensuring uninterrupted power supply while maintaining grid compatibility.	MATLAB simulations	The proposed system achieved 99.6% efficiency with enhanced voltage gain, ensuring efficient power generation, stable operation, and successful grid integration. The system contributed to sustainable EV charging by optimizing energy extraction and supporting grid stability through bidirectional power flow.
[30]	Review the development of photovoltaic-powered EV charging stations, exploring the potential for economic growth and a decentralized energy system by increasing EV charging stations and advancing sustainable transportation infrastructure.	MATLAB simulations	The study found energy consumption ranging from 0.139 to 0.295 kWh/km and a cost of energy ranging from 0.0032 to 0.5645 $/kWh. The average payback period for PV-powered EV charging stations was between 1 and 15 years, highlighting the economic viability of the application.

Considering the imperative and significance of EVs development, along with the findings from the aforementioned studies and other research conducted by the authors, it's apparent that to date, no comprehensive study focusing on 3E aspects has been undertaken in Iran. Specifically, there hasn't been an investigation aimed at determining the most advantageous configuration of an on-grid solar-wind-based system. Conducting sensitivity analysis on effective parameters, using the most recent costs of used equipment, using real prices of electricity purchase/sale tariffs from/to the national power grid, calculating return on investment time for the optimal system under study, and using real and up-to-date annual interest rate data are among the other benefits of the present work. With respect to the practical application of this case study's findings to diverse global regions with varying climatic conditions, it's noteworthy to highlight that the analytical approach, physical justifications applied, as well as the algorithm and software utilized in this study, can be adapted for use in any region, regardless of its climate. The authors expect the results obtained and the study's suggested analytical method to be efficient in diminishing the rate of pollution in cities, enhancing socio-economic development, and promoting public comfort.

3. Study Area

As seen in Figure 3, Shahrekord is placed in the central part of Iran and the capital city of Chaharmahal and Bakhtiari Province. This region is situated within the geographical coordinates of 32.32° N latitude and 50.86° E longitude. With its elevation between 2050m and 2310m above sea level, Shahrekord is the highest capital city in Iran. There are multiple big industries and prominent factories in Shahrekord, leading to the considerable consumption of energy and fossil fuels for transportation in this city with a population of around 200,000 people. This is why Shahrekord was selected for study in this work.

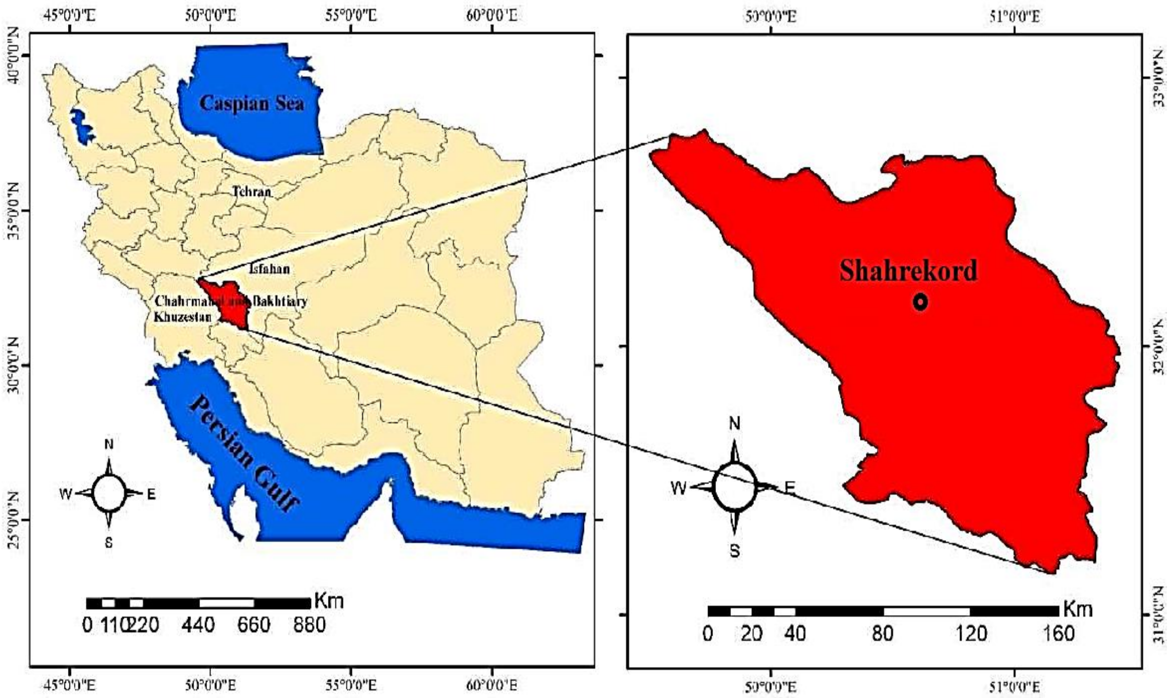


Fig. 3. Location of Shahrekord in Iran

4. Data Required for Simulation

This study employed simulations conducted in HOMER software, renowned for its effectiveness in designing electricity microgrids [31, 32] and optimizing hybrid renewable energy systems (RES). HOMER offers features such as accurate system simulation at various time intervals, cost estimation, and optimization rate determination [33, 34].

The performance of each component in the system is governed by equations within the HOMER software. These equations encompass factors such as solar cell energy production [35], wind turbine performance [36], battery behavior [37], power exchange with the national power grid [38], and economic calculations [39-41], as outlined in equations 1 to 4, respectively.

$$P_{pv} = Y_{pv} \times f_{pv} \times \frac{\overline{H_T}}{\overline{H_{T,\,STC}}} \tag{1}$$

This equation calculates the power output of the PV system, where:

P_{pv} is solar power production. Y_{pv} is the rated capacity of the PV system. f_{pv} is the efficiency factor of the PV system. $\overline{H_T}$ is the average solar radiation (in kWh/m²). $\overline{H_{T.STC}}$ is the standard test conditions (STC) for solar radiation.

$$P_{WTG} = \frac{\rho}{\rho_0} \times P_{WTG.\,STP} \tag{2}$$

This calculates the power output of a wind turbine, where:

P_{WTG} is the wind turbine's power output. ρ is the air density at the installation site. ρ_0 is the reference air density at sea level (usually 1.225 kg/m^3). $P_{WTG.STP}$ is the wind turbine power output under standard test conditions.

$$P_{batt.\,cmax} = \frac{\mathrm{Min}\left(P_{batt.\,cmax.kbm}, P_{batt.\,cmax.mcr}, P_{batt.\,cmax.mcc}\right)}{\eta_{batt.c}} \tag{3}$$

This equation calculates the maximum charge power of the battery, where:

$P_{batt.\,cmax}$ is battery maximum charge power. $P_{batt.\,cmax.kbm}, P_{batt.\,cmax.mcr}, P_{batt.\,cmax.mcc}$ are different maximum charge power limits (e.g., from the battery's specifications or operational constraints). $\eta_{batt.c}$ is the efficiency of the battery charger.

$$C_{grid.\,energy} = \sum_{i}^{rates}\sum_{j}^{12} \begin{cases} E_{net\ grid\ purchases.i.\,j} \cdot c_{power.i} \\ if E_{net\ grid\ purchases.i.\,j} \geq 0 \\ E_{net\ grid\ purchases.i.\,j} \cdot c_{sellback.i} \\ if E_{net\ grid\ purchases.i.\,j} < 0 \end{cases} \tag{4}$$

This calculates the cost of energy from the grid, where:

$C_{grid.\,energy}$ is the grid energy cost. $E_{net\ grid\ purchases.i.j}$ is the net energy purchased or sold from the grid in a given period. $c_{power.i}$ is the cost of power when purchasing from the grid. $c_{sellback.i}$ is the cost when selling excess energy back to the grid.

$$NPC = \frac{C_{ann,\,total}}{CRF\left(i,\,R_{proj}\right)} \tag{5}$$

This equation calculates the net present cost, where:

NPC is the net present cost [42]. $C_{ann,total}$ is the total annual cost. $CRF\ (i.R_{proj})$ is the capital recovery factor, calculated as:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

This is the formula to calculate the capital recovery factor, where:

CRF is the capital recovery factor [42]. i is the interest rate. N is the number of periods.

$$i = \frac{i' - f}{1 + f} \tag{7}$$

i is the interest rate adjustment. This adjusts the interest rate based on the rate of inflation.

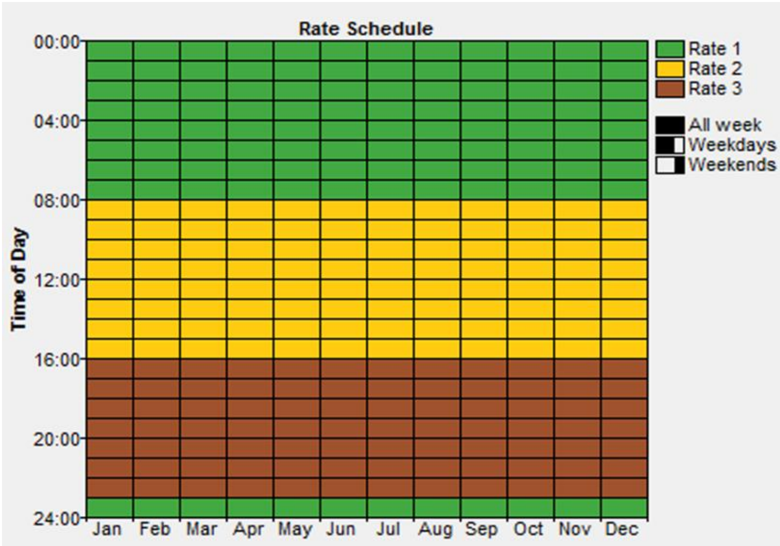
$$COE = \frac{C_{ann,\,total}}{E_{Load\ served}} \tag{8}$$

COE is the actual cost to buy energy, and it becomes a major concern for the public and utilities as the demand for power from RESs increases. Utilities may become reluctant to purchase more renewable energy than they are required to purchase if the COE is too high [43]. $C_{ann.total}$ is the total annual cost. $E_{Load\ served}$ is the total energy served to the load.

In this work, the annual interest rate was 18% [44], the useful life of the project was 20 years, the rate of penalty of pollutants was zero [45], the elevation from the sea level was 2180 m [46], and the daily electricity consumption was 396 kWh, with a peak value of 66 kW. In Figs. 4 to 7, three-time tariffs of the purchase and sale of electricity from the national power grid, the mean rate of monthly radiation [47], the mean rate of monthly wind velocity [47], and the rate of electricity required for 24 hours are illustrated, respectively.

The electricity consumption in this study is categorized into three tariff periods: off-peak, mid-peak, and peak hours. The purchase prices for each of these periods were obtained through direct consultation and inquiry with experts from the regional electricity distribution company. Furthermore, the electricity selling price to the grid was calculated based on the official feed-in tariff for renewable energy, using the monthly average values of this rate over the course of a year.

The price of equipment used and other associated features to supply electricity to EVs CS are presented in Table 2.



Rate	Price($/kWh)	Sellback($/kWh)
Rate 1	0.050	0.318
Rate 2	0.070	0.445
Rate 3	0.120	0.763

Fig. 4. Different rate prices of national power grid in Iran

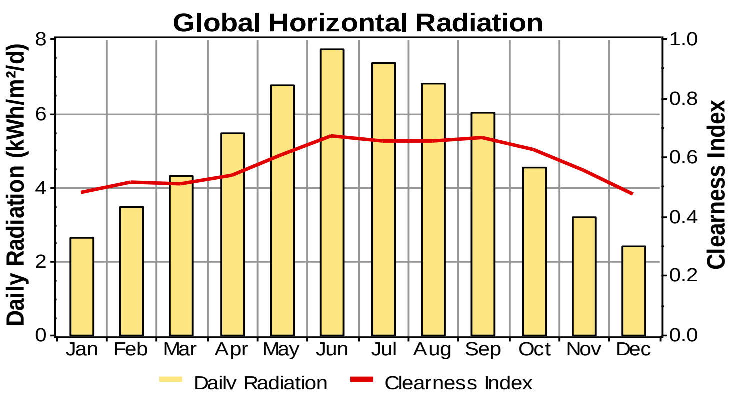


Fig. 5. Solar Radiation of Shahrekord

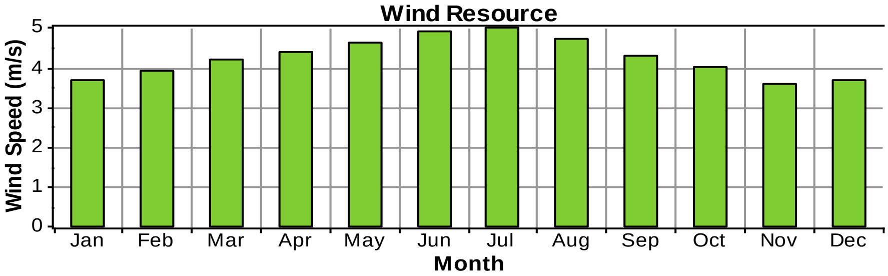


Fig. 6. Wind resource of Shahrekord

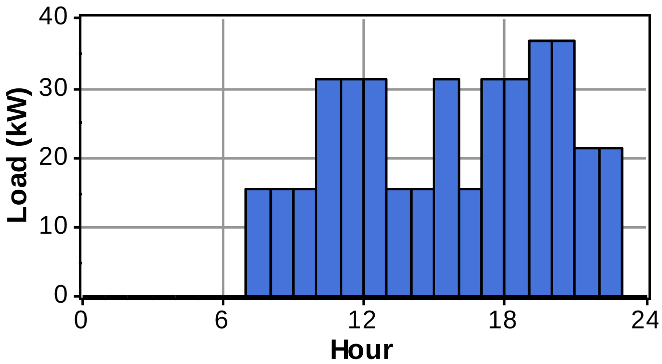


Fig. 7. Electricity daily profile of EV CS

Table 2. Information on the EV station system under study

Equipment	Cost ($)			Size (kW)	Other information
	Capital	Replacement	O & M		
PV [48]	1000	1000	5	0-50	Lifetime: 25 years Derating factor: 80% Ground reflectance: 20%
Battery T-105 [49]	174	174	5	0-50	Nominal Voltage: 6 Nominal capacity: 225Ah Lifetime throughput: 845 kWh
WES Tulipo (2.5 kW AC) [50]	5000	4000	50	0-10	Lifetime: 15 years Hub height: 25 m
Converter [51]	200	200	10	0-50	Lifetime: 10 years Efficiency: 90%

To calculate the emissions resulting from electricity consumption from the national grid, standard emission factors reported by the Iran Power Generation, Transmission and Distribution Company (Tavanir) and related national sources have been used. Specifically, for every kWh of electricity consumed from the grid, 632 g of CO_2, 2.74 g of SO_2, and 1.34 g of NO_x are emitted [52].

5. The Ev Cs Under Study

A schematic of the station under examination is illustrated in Fig. 8. The EV under examination has a 93.4 kWh battery that needs 6 hours for full charging. The station is equipped with two nozzles, each with a daily capacity of charging two EVs. It is worth nothing that a total of 5.6 kW power has been dedicated for lighting from 7 pm to 11 pm. As the system under examination is connected to the national power grid, any excess electricity is sold back to the grid during hours when EV charging is not in demand.

6. Simulation Results

The result of the best possible configuration is depicted in Table 3. As illustrated, the most economically optimal system has the net present cost of $58644, using a 50 kW solar panel, a 25 kW wind turbine (10×2.5 kW wind turbines), a

40 kW electrical converter, and the national power grid. Each kWh of the generated power costs $0.058, a value determined based on the off-peak rates of the national power grid, as illustrated in Figure 4. Based on Fig. 9, which indicates the mean rate of monthly electricity generation, around 66% of the electricity has been generated from wind and solar energy sources. Based on Fig. 9, the minimum rate of electricity consumption from the national power grid happens in June and July, while the maximum rate is observed in December and January.

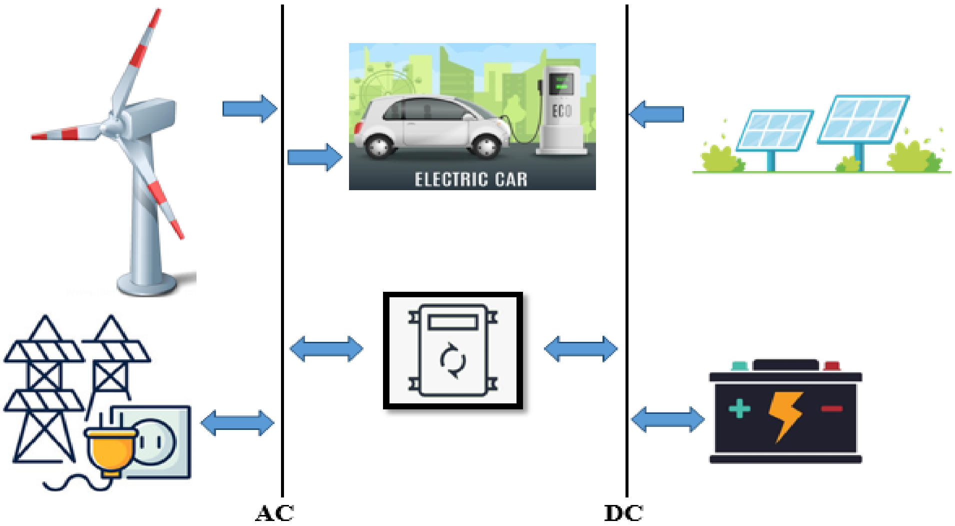


Fig. 8. Schematic of EV CS

Table 3. Results of optimal configurations

Grid	PV	Wind	Battery	Conv.	PV (kw)	WESS	T-105	Conv. (kw)	Grid (kW)	Initial capital ($)	Operation cost ($/year)	Total NPC ($)	COE ($/kWh)	Ren. Frac.
✓	✓	✓		✓	50	10		40	1000	108000	-9221	58644	0.058	0.66
✓	✓	✓	✓	✓	50	10	5	40	1000	108870	-9061	60367	0.060	0.65
✓									1000	0	13543	72490	0.094	0.00
✓			✓	✓			5	5	1000	1870	13683	75114	0.097	0.00
✓		✓				2			1000	10000	12335	76024	0.097	0.07
✓	✓			✓	5			5	1000	6000	13105	76149	0.098	0.05
✓	✓		✓	✓	5		5	5	1000	6870	13161	77316	0.100	0.05
✓		✓	✓	✓		2	5	5	1000	11870	12514	78852	0.100	0.07

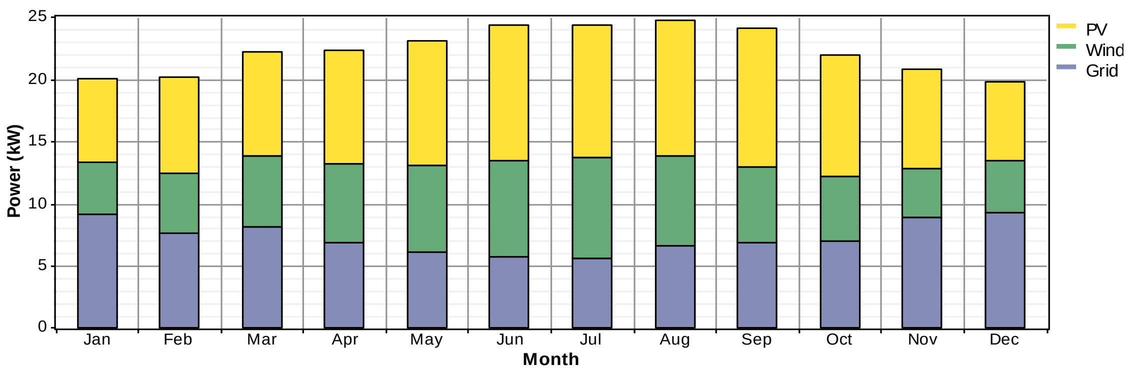


Fig. 9. The mean monthly electricity output.

Owing to the results, a total of 80094 and 51420 kWh electricity are generated annually from solar panels and wind turbines, respectively. Moreover, a total of 64048 kWh electricity is purchased for the national power grid.

Table 4 displays the power transaction with the national power grid. According to the illustration, a total of 42,896 kWh of power is sold to the national power grid annually. The highest and lowest power sales to the grid are recorded in July (5,171 kWh) and December (2,050 kWh), respectively. Notably, in June and July, the amount of power sold to the national power grid surpasses the purchased power, resulting in a negative net rate of power purchased from the grid. Overall, 21,153 kWh of power is purchased annually from the national power grid.

The generation of electricity by the national power grid is related to the emission of pollutants. Table 5 presents the rate of pollutants generated by the system under investigation. According to the results, a total of 13369 kg CO_2, 58 kg SO_2, and 28.3 kg NO is generated annually.

Table 5. Emissions of optimal configuration

Pollutant	Emissions (kg/yr)
CO_2	13,369
CO	0
Unburned hydrocarbons (UHC)	0
Particulate matter	0
SO_2	58
NO_x	28.3

Figure 10 indicates a comparison of an optimal system (current case) with the state in which all the power required is generated by the national power grid (base case). The point to consider is that the duration for the return on capital of the system is about 4.6 years, i.e., a duration that is spent for settling the cost of purchasing renewable equipment. At the end of the 20th years of project lifetime, the optimal system (current case) has a positive level of $78000, while the scenario of the national power grid has the level of $-270000, indicating that a total of $348000 revenue can be earned if using the optimal system (current case) instead of the national power grid (base case).

Table 4. Results of power exchange with the national power grid

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchased (kWh)
Jan	6787	2283	4503
Feb	5100	2375	2726
Mar	6062	3125	2937
Apr	4933	3463	1470
May	4544	4486	58
Jun	4121	4692	-570
Jul	4163	5171	-1007
Aug	4924	4655	268
Sep	4961	4420	541
Oct	5207	3558	1649
Nov	6399	2618	3781
Dec	6847	2050	4797
Annual	64048	42896	21153

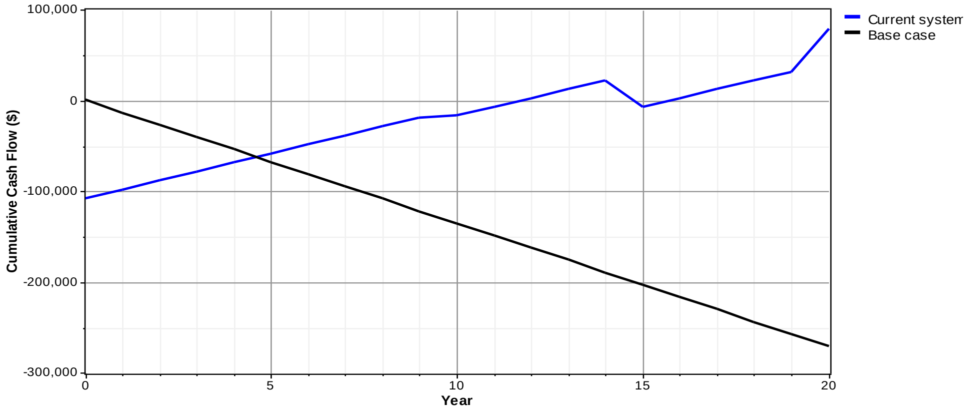


Fig. 10. Current System Compared to Base Case

In light of the uncertainty surrounding factors such as wind speed and solar radiation, a sensitivity analysis was conducted on these variables. Figures 11 and 12 depict the effects of wind speed and solar radiation on the LCOE and the rate of CO_2 emissions, respectively.

According to Figure 11, an increase in solar radiation and/or wind speed leads to a higher rate of renewable energy generation, resulting in increased power sales to the national power grid and a considerable reduction in the LCOE. For example, at a wind speed of approximately 15 m/s and solar radiation of 15 kWh/m^2-day, the LCOE is -$0.0271 per kWh.

Figure 12 illustrates that higher wind speed and solar radiation correspond to increased renewable electricity generation and subsequent addition to the grid, resulting in a substantial decrease in CO_2 emissions. For instance, at a wind velocity of 15 m/s and solar radiation of 15 kWh/m2-day, the CO_2 emission rate is -22,635 kg/yr.

Observing both figures, it's evident that an increase in wind velocity has a greater impact on reducing pollutants and/or the LCOE compared to an increase in the intensity of solar radiation.

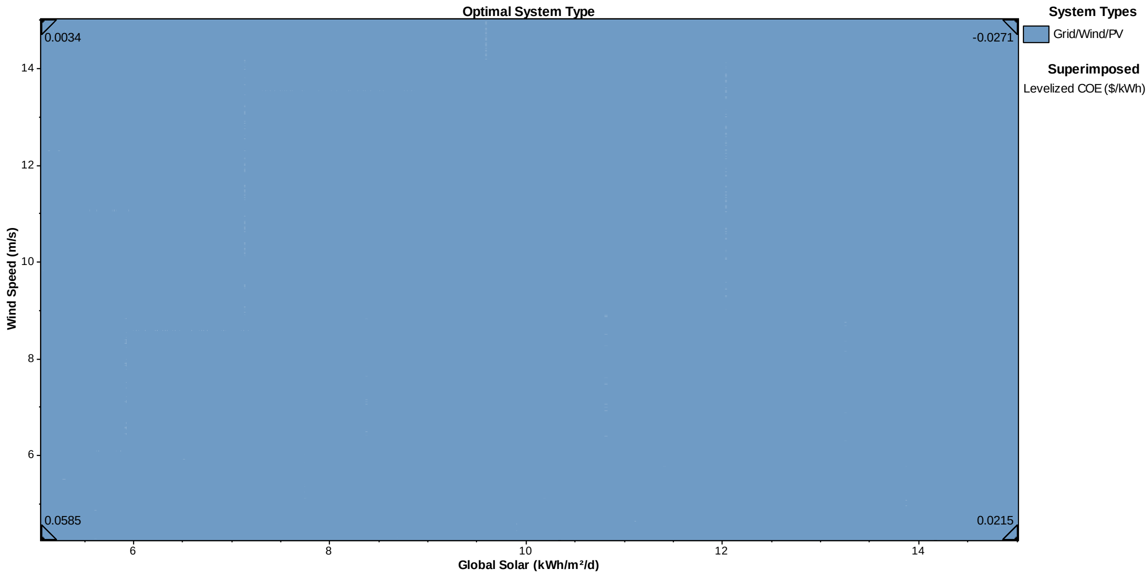


Fig. 11. Sensitivity analysis on LCOE

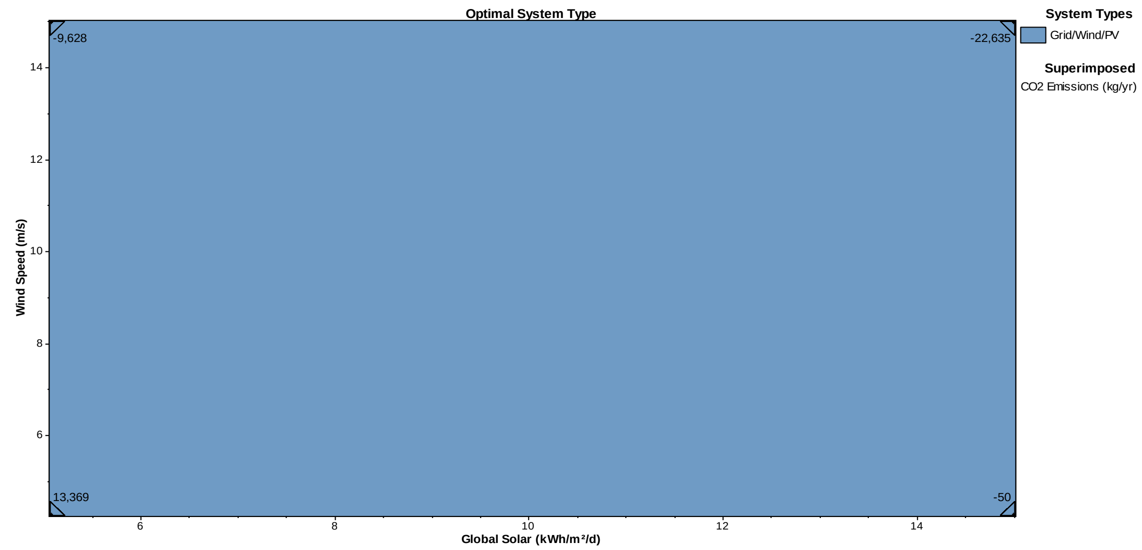


Fig. 12. Sensitivity analysis on CO_2 emissions

Under the current conditions—namely a solar radiation intensity of 5.06 kWh/m²/day and a wind speed of 4.25 m/s—sensitivity analysis was conducted for three different scenarios: Grid–Wind Turbine–PV (Scenario 1), Grid–Wind Turbine (Scenario 2), and Grid–PV (Scenario 3). This analysis examines the effect of ±10% variations in key techno-economic-environmental parameters on the LCOE value across all three scenarios, both intra-scenario and inter-scenario. In this study, linear regression was used for sensitivity analysis to predict the LCOE and compute the relative changes resulting from ±10% fluctuations in key parameters. Figure 13 illustrates the impact of six different parameters on the LCOE in all three scenarios.

In the first row of Fig.13, a prominent and wide chart is observed, indicating a stronger effect of parameter changes on LCOE. The bars related to the increase and decrease of CO_2 emission, Payback time, and Renewable fraction are the tallest, demonstrating that these parameters play a pivotal role in determining the final cost of electricity generation in this scenario. Furthermore, the negative impact of reducing the Initial cost is significantly greater than the effect of increasing it, highlighting the high elasticity of LCOE with respect to initial investment. Values ranging from 12% to 17% indicate that this system is sensitive yet responsive and dynamic to its input parameters.

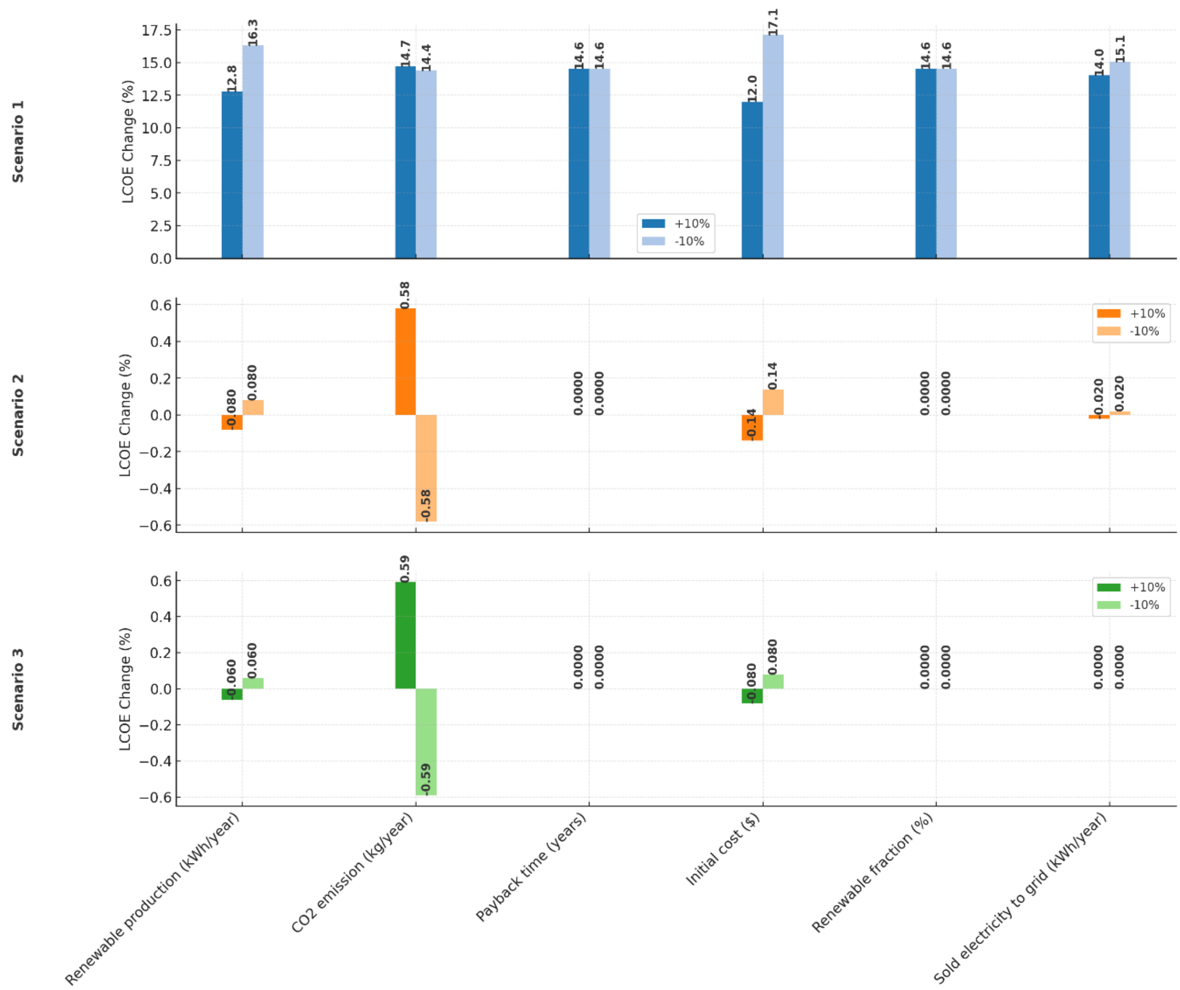


Fig. 13. Comparative sensitivity analysis chart showing the effect of techno-economic parameters on LCOE in three EV charging station design scenarios

In Scenario 2, the values are generally smaller than in Scenario 1, which is due to the smaller scale of RESs in this scenario. Nevertheless, changes in LCOE remain notably dependent on parameters such as CO_2 emission and Payback time. Unlike Scenario 1, in this case, changes in Renewable production have a lesser impact since its absolute value is much lower. The smaller bars in this scenario still indicate small yet meaningful differences. Overall, this scenario behaves more stably than Scenario 1 against changes in the parameters.

In Scenario 3, the effect of parameter variations on LCOE is noticeably lower, and the most prominent difference compared to the other two scenarios is the significant compression of changes within a range of less than 1%. In this scenario, CO_2 emission and Payback time still have the greatest impact, but their influence is nearly one-tenth of that in Scenario 1. This may be due both to higher dependency on the grid and the absence of a wind source, which simplifies the system dynamics and makes the output less volatile and more stable with respect to its inputs.

Overall, Fig.13 shows that Scenario 1 exhibits the greatest sensitivity elasticity and the strongest mutual influence between parameters and LCOE. In contrast, in Scenarios 2 and 3, by eliminating one of the renewable sources, not only has the share of clean energy declined, but the system's sensitivity has also decreased, making the LCOE output more stable against parameter changes. Moreover, the way the system responds to increases or decreases in each parameter—such as asymmetry in Initial cost or CO_2 emission—clearly reveals the strengths and weaknesses of each configuration.

7. Conclusion

Electric vehicle CSs that utilize RESs not only do not cause air pollution, but can also improve the load curve, enhance grid security, and achieve economic advantages by modifying the maximum load of the grid. In the current work, using HOMER software, sensitivity analysis, as well as a 3E assessment of a wind-solar energy-based CS, was conducted in Shahrekord, Iran. The results are summarized as follows:

- In an economically optimal system, the annual electricity generation from solar panels totals 80,094 kWh, while the electricity generated from wind turbines amounts to 51,420 kWh.
- An economically optimal system has a COE value of 0.058 $/kWh.
- The LCOE value for solar electricity and wind electricity in an economically optimal system is respectively 0.119 $/kWh and 0.2 $/kWh.
- In an economically optimal system, the annual CO_2 emissions amount to 13,369 kg as a result of the partial supply of power required from the national power grid.
- Sensitivity analysis results indicated that for a wind velocity of 15 m/s and solar radiation of 15 kWh/m^2-day, the COE value is -0.0271 $/kWh and the rate of CO_2 emission is -22635 kg/year.
- The duration for return on capital and the value of net income after 20 years are equal to 4.6 years and $78000, respectively, as compared economically optimal system with a system connected to the national power grid.

Unfortunately, Iranian carmakers have not yet had serious and significant activity in the production of EVs. It is clear that in order to expand the use of EVs, a competitive market must be created. In addition, with the help of government subsidies, the price of EVs should be such that consumers can be encouraged to buy. Therefore, considering subsidies for the purchase of EVs in the annual budget can be one of the best supportive policies in Iran. Other policies, including tax breaks, could also be helpful in expanding the use of EVs in transportation.

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