HYDROGEN, FUEL CELL & ENERGY STORAGE

Solar and Wind-Powered Charging in Tehran: A New Era for Electric Vehicles and Hydrogen Bikes

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Abstract

The development of renewable- powered EV charging stations in Tehran is crucial for reducing air pollution, improving urban air quality, decreasing reliance on fossil fuels, and enhancing energy sustainability. A simulation was conducted for the first time, including three fast and slow charging modes, as well as a green hydrogen production unit for bicycles. The system, integrated with the national grid, prices surplus electricity sales based on the green energy market while penalizing pollutant emissions. Using HOMER software and NASA's 20-year climate data, the study found that wind energy economically outperforms solar energy in Tehran. The optimal system uses 51% wind and 45% solar energy, with a total reliance of 96% on renewables. The costs are 0.087 \$/kWh for electricity and 292.1 \$/kg for hydrogen production. Moreover, by selling the surplus electricity to the national grid, it prevents the annual emission of approximately 967.4 tons of various pollutants- including 961.2 tons/year of CO_2, 4.2 tons/year of SO_2, and 2 tons/year of NO_x. The broader implications of this study include promoting the use of renewable energies in urban infrastructure, reducing environmental pollution on a large scale, and providing a scalable model for sustainable energy systems in similar urban areas worldwide. Integrating renewable energy into EV charging stations offers a scalable and sustainable model for urban development. Addressing challenges like high costs and grid stability requires supportive policies, including subsidies and incentives, while future research should center on optimizing renewable systems, improving green hydrogen production, and enhancing smart grid integration.

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1 Introduction

In 2023, global sales of EVs reached approximately 14 million, marking a 35% increase compared to the previous year. This surge brought the total number of EVs on the road worldwide to over 40 million (Figure 1) [1]. As shown in Figure 1, another noteworthy observation is that battery electric vehicles (BEVs) accounted for 70% of all EVs in 2023.

The large-scale adoption of EVs depends on the simultaneous availability of accessible and affordable charging infrastructure. EV charging stations are essential for promoting clean transportation by facilitating the recharging of EVs. Previously, EV owners preferred to charge their vehicles at home. However, nowadays, EV charging stations need to be installed both in urban and suburban areas to enable continuous vehicle use [2]. Currently, there are around 4 million public charging stations worldwide, with the number expected to reach 15 million by 2030.

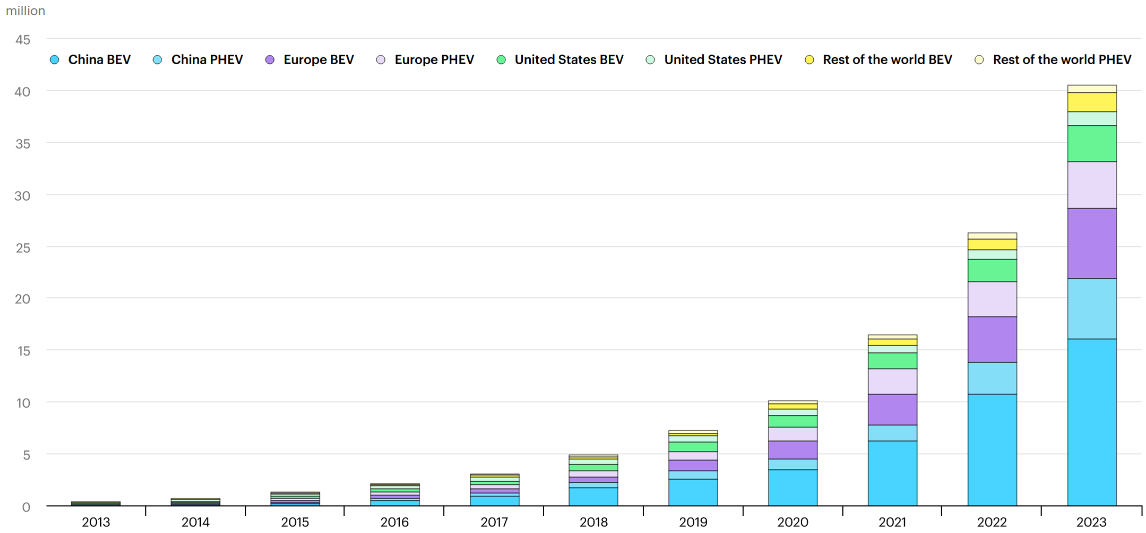


Fig. 1. Total EVs on roads worldwide.

Economically, the high initial cost of EVs and the lack of financial incentives for buyers reduce their attractiveness in Iran. Additionally, public awareness of the benefits of EVs remains limited, and many consumers doubt their reliability and performance [3]. Finally, the environmental challenges associated with the production and recycling of batteries could also hinder the growth of the EV market. Nevertheless, the Iranian government is making efforts to improve conditions for EV adoption by encouraging domestic production and introducing new EV models to the market [4].

In Iran, the adoption of EVs faces significant challenges that hinder their expansion. One major obstacle is the dominance of state-owned car manufacturers, which produce around 80% of vehicle production, and the government's reluctance to import EVs due to vested interests. Additionally, the lack of a strong policy framework and the shortage of incentives for consumers have slowed the EV adoption. Inadequate infrastructure, such as the limited number of charging stations and constraints on the power grid, are also among the key obstacles to progress in this area [5–7].

The following reviews recent studies on the evaluation of EV charging stations. Particular attention is given to thoroughly examine previous studies to highlight the scientific gap that this current study aims to fill.

In 2023, Karmaker et al. [8] examined an energy management system for renewable energy-based EV charging stations. Using MATLAB SIMULINK, they studied biogas and solar energy. The results indicated that their proposed algorithm reduced energy costs by up to 74.67% compared to existing fixed-rate tariffs, decreased greenhouse gas emissions, and resulted in relatively short payback periods for charging station owners.

In 2023, Ihm et al. [9] optimized the design of an EV charging station using renewable energy in South Korea. Using HOMER software, they evaluated system performance across renewable energy fractions of 0%, 25%, 50%, 75%, and 100%. The results showed that the PV-Battery-Grid configuration was the most suitable, with a renewable energy fraction below 25% being economically and environmentally optimal.

In 2023, Shafiei and Marzbali [10] designed a fast EV charging station powered by renewable energy. They used a combination of fuzzy neural networks with the particle swarm optimization algorithm. Two scenarios were examined: one with the wind turbine owned by the station and one with the wind turbine owned by the grid. The results showed cost reductions of 17.85% and 3.31% for the first and second scenarios, respectively.

In 2023, Barman et al. [11] reviewed various methods for integrating renewable energy with EV technology. Their main goal was to analyze and evaluate different smart charging approaches to improve the efficiency and sustainability of electric transportation systems. They first reviewed available renewable energy sources for EV charging and leading countries, then examined storage technologies, and finally discussed existing challenges, standards, and network security.

In 2023, Bilal et al. [12] conducted a techno-economic assessment of EV charging stations using renewable energy in India. Using the Modified Scalp Swarm Algorithm, their results indicated that New Delhi, with a total net present cost (NPC) and cost of energy (COE) of $14,853.63 and $0.0051 per kWh respectively, was the most suitable location. This assessment was based on the use of 120 solar cells 325W and 310 wind turbines 650W. 64.5% of the electricity was produced by wind turbines, 33.5% by solar cells, and the remainder by the grid.

In 2023, Allouhi and Rehman [13] optimized and conducted a sensitivity analysis on a grid-connected hybrid renewable energy system for a supermarket with an EV charging station. They used HOMER software to carry out simulations across various locations in Morocco. The results showed that the Dakhla station, which is windy, with a renewable energy fraction and COE of 71.66% and $0.0841 per kWh respectively, was the most suitable station. The optimal economic system included 107 kW of solar cells, 300 kW of wind turbines, 12 batteries, and a 65 kW inverter.

In 2023, Mohan and Dash [14] examined a renewable energy-based DC microgrid with an EV charging station. They used the particle swarm optimization (PSO) and sparrow search algorithm (SSA) in MATLAB for simulations. The results indicated that SSA reduced electricity costs by approximately 7.8% compared to PSO.

In 2023, Hasan et al. [15] performed a techno-economic analysis of an EV charging station at an airport in Bangladesh. Using fuzzy logic, they proposed an electric load of 10.54 MWh per day. The results showed that among the four scenarios examined, the wind turbine-solar cell-grid scenario, with an electricity production cost of $0.041 per kWh and a renewable energy fraction of 84.3%, proved to be the most suitable. Considering a charging tariff of $0.14 per kWh, the estimated annual profit was $0.22 million. Pollutant emissions were reduced by 75% compared to the grid-only scenario.

In 2024, Razeghi et al. [16] used ArcGIS software to identify optimal locations for EV charging stations in Khuzestan province, southwest Iran. They conducted technical, economic, environmental, and geological assessments. The results showed that 90% of the cities in this province have the potential to establish EV charging stations using solar energy, especially Mahshahr, which could supply up to 90.55% of the required charging energy through solar power. Additionally, the region has the capacity to convert 11% of vehicles to electric by 2040, resulting in a reduction of 30 tons of pollutants.

In 2024, Abdel-Basset et al. [17] evaluated the optimal locations for vehicle charging stations in Egypt. Their study assessed the impact of 6 main and 19 sub-factors on the optimal location selection. They used DEMATEL and COPRAS methods for ranking. Among the six candidate locations, the most suitable site was ultimately identified in the city of Zagazig.

Based on the reviewed studies, it is observed that all prior research were performed in different climate conditions. While some studies differed in methodology, others pursued different objectives. Additionally, previous studies did not address key aspects such as hydrogen production, the inclusion of pollutant penalties, and the presence of multiple charging lines (DC fast, AC fast, and AC slow) – all of which are considered as scientific gaps and are addressed in the present study. Using HOMER software, this study conducts a technical, energy, economic, and environmental assessment of a wind and solar energy-based EV charging station in Tehran. The station is designed to support six types of electric vehicles available in the Iranian market, and the feasibility of hydrogen production for new-generation hydrogen bicycles is also examined.

2 Software under Review

HOMER software is a powerful tool for designing and optimizing electric vehicle charging stations, presenting its comprehensive modeling of hybrid systems, cost and efficiency optimization, support for fast and slow charging modes, and user-friendly reporting features [18–21].

In the present research, HOMER software was used for energy-economic-environmental simulations. The reasons for selecting this software are as follows [22–24]:

- It is a specialized tool for simulating hybrid renewable energy systems.
- It facilitates economic analysis of systems using criteria such as net present cost.
- It has the capability to integrate long-term climate data (such as 20-year NASA data) and load profiles.
- It enables the comparison of multiple system scenarios and the selection of the optimal option in terms of economic and environmental aspects.
- It has global credibility and is widely used in renewable energy research.

HOMER software is designed to accurately simulate hybrid energy systems. The reason why the two primary loads are defined hourly (24 hours) and the deferrable load is recorded on a monthly average basis is due to the different needs of these load types and their roles in the analysis:

- *Primary Load*: These loads represent sensitive and uninterrupted needs that must be supplied instantaneously without delay. Therefore, they should be defined hourly to accurately simulate and analyze the precise consumption patterns over a 24-hour period.
- *Deferrable Load*: These types of loads, such as water pumps or energy storage, are more flexible, allowing their energy needs to be deferred for specific periods. Therefore, a monthly average is sufficient to optimize their energy consumption without the need for hourly precision.

This difference in load definitions helps HOMER to accurately optimize each load type based on its specific characteristics and needs. Figure 2 shows a schematic of the designed charging station. As illustrated, the hybrid system under review includes solar panels and wind turbines to generate renewable electricity. An electrical converter is used to convert the renewable direct current (DC) power to the alternating current (AC) power needed. Additionally, as a backup, the system is connected to the national power grid, allowing it to purchase electricity when needed and sell excess electricity to the grid during periods of high production.

3 Methodology

Tehran, as the capital of Iran, located at 35.41° N latitude and 51.23° E longitude with a population of approximately 9.8 million people [25], faces a severe air pollution problem. This pollution, caused by the use of fossil fuels in traditional vehicles, underscores the need for EVs to reduce emissions, improve air quality, and ensure the public health. Developing the infrastructure related to these vehicles is essential to mitigate the detrimental environmental effects.

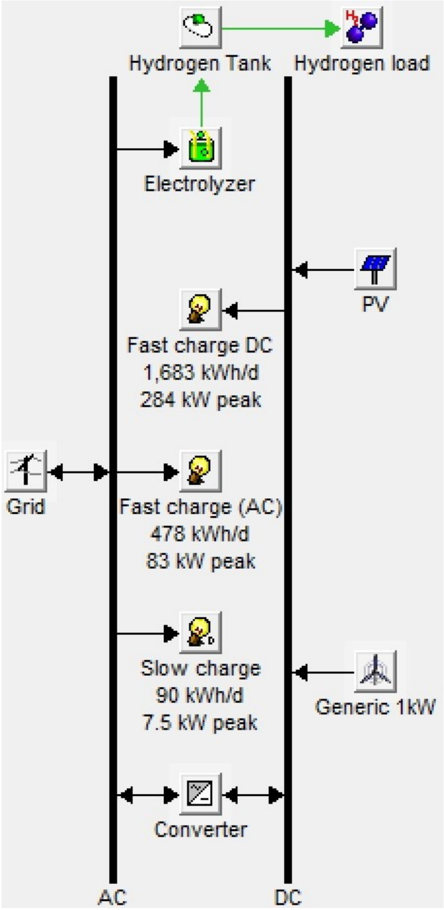


Fig. 2. Schematic of the system under study.

Tehran is the most suitable location in Iran for assessing the feasibility of installing renewable energy power plants for EV charging stations for the following reasons:

- As Iran's capital and its economic and cultural hub, Tehran experiences high traffic. This increases the number of EVs in the city and consequently the need for more charging stations.
- Tehran has extensive public road networks and high-capacity power transmission lines, providing the necessary infrastructure for installing renewable energy power plants.
- Due to its economic and political significance, Tehran is a hub for major investments and support in renewable energy projects.
- Tehran hosts research centers and universities active in the field of renewable energy and modern technologies, which can actively contribute to EV charging projects.

According to recent reports, Tehran has approximately 15 EV charging stations, including both fast and slow chargers [26]. Most of these charging stations are in central areas of the city, near large shopping centers and public parking lots [27]. Figure 3 shows one of these charging stations installed in Azadi Square [26].

Fig. 3. View of a charging station installed in Tehran [26].

Fast charging typically takes about 30 minutes to an hour to charge an EV battery for up to 80%, while slow charging may take several hours, usually between 6 to 8 hours for a full battery charge [28, 29].

Figures 4 and 5 respectively show the location of Tehran on the map of Iran. As indicated by these figures, Tehran has moderate potential for both wind and solar energy. Therefore, it is more evident to assess which energy source is more suitable, whether a combination of both is preferable, or if relying on the national power grid offers a more cost-effective solution.

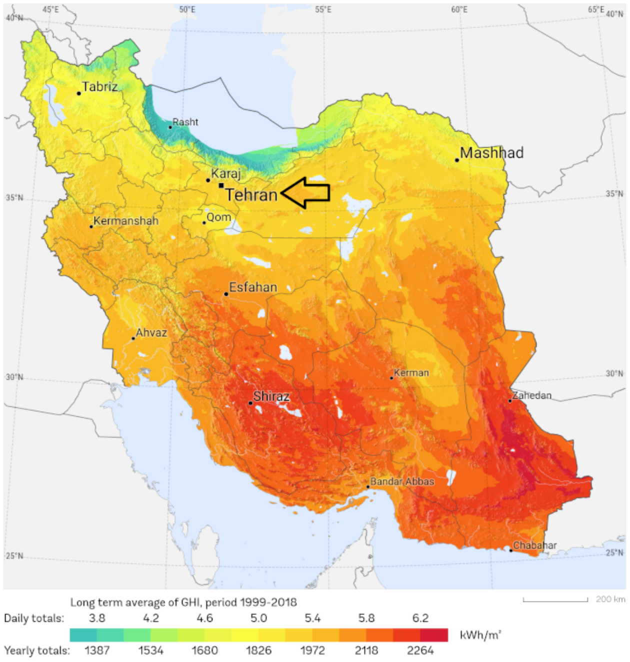


Fig. 4. 20-year average solar radiation map of Iran and the location of Tehran on it [30].

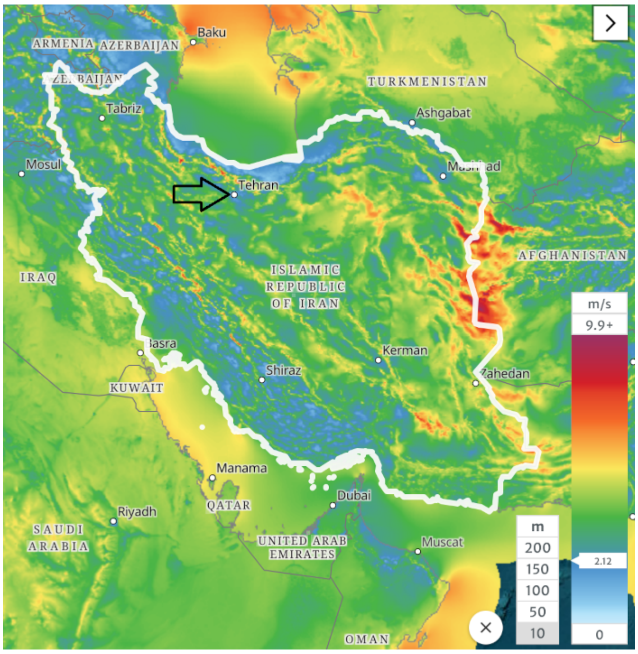


Fig. 5. Wind speed map of Iran at 10 m elevation and the location of Tehran on it [31].

It should be mentioned that implementing a wind and solar power generation system for EV charging stations in Tehran faces several challenges. Among these challenges are policy barriers, including a lack of supportive policies, limited financial incentives, and inconsistent regulations in the development of renewable energies. Additionally, infrastructure limitations such as the absence of a smart grid and the necessary facilities for integrating wind and solar energy into the national grid, as well as the high costs of installation and maintenance of these systems, pose significant obstacles. Finally, economic limitations, including the high initial cost of equipment and technology, as well as limited access to financial resources, impact the implementation of this project. However, offering policy incentives, creating appropriate infrastructure, and securing necessary funding through domestic and foreign investments can help reduce these barriers and support the successful implementation of this system.

The HOMER software simulates various scenarios and finds the optimal configuration by solving the governing equations for the performance of each component of the hybrid renewable energy system. Below, Equation (1) shows the amount of electricity generated by solar cells [32], Equation (2), the amount of electricity generated by wind turbines [33], Equation (3), the sizing ratio of the electrical converter [34], Equation (4), the exchange of electricity with the national grid [35], Equation (5), the efficiency of the electrolyzer [34], Equation (6), the autonomy of the hydrogen storage tank [34], Equation (7), the cost per kWh of electricity produced [36], and Equation (8), the net present cost of the project [37].

$$P_{\mathrm{PV}} = f_{\mathrm{PV}}\, Y_{\mathrm{PV}}\, \frac{I_T}{I_s} \tag{1}$$

$$P_{\mathrm{wind}} = \frac{1}{2} \tau\, \rho\, C_p A \sum_{x=1}^{j} f_{(v)} v_x^3 \tag{2}$$

$$R = \frac{\text{The size of the DC electricity producer's renewable equipment}}{\text{The inverter size}} \tag{3}$$

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

$$\eta_{\text{electrol}} = \frac{\text{The energy content (based on HHV) of the hydrogen produced}}{\text{The amount of electricity consumed}} \tag{5}$$

$$A_{\text{htank}} = \frac{Y_{\text{htank}}\, \mathrm{LHV}_{\mathrm{H_2}}\, (24\,\mathrm{h/d})}{L_{\text{prim.ave}}\, (3.6\,\mathrm{Mj/kWh})} \tag{6}$$

$$\mathrm{COE} = \frac{C_{\text{A.cap}} + C_{\text{A.rep}} + C_{\text{A.O\&M}}}{E_s} \tag{7}$$

$$\mathrm{NPC} = \frac{C_{\text{A.cap}} + C_{\text{A.rep}} + C_{\text{A.O\&M}}}{\dfrac{(\frac{i-f}{1+f})(1+\frac{i-f}{1+f})^n}{(1+\frac{i-f}{1+f})^n - 1}} \tag{8}$$

The assumptions in this study are as follows:

- The simulation time step is set to one hour.
- There are no specific limits for pollutant emissions.
- The effect of temperature on the performance of photovoltaic cells has not been considered.
- Optimal azimuth is not used, and the cells are simply oriented south.
- The ground reflectance factor is considered to be 20%.
- The derating factor is set to 80%.
- The national grid emits three major pollutants: CO_2, SO_2, and NO_x.

4 Input Data

Fast charging in EVs is done with high voltage and current, allowing for less time to charge. In contrast, slow charging uses lower voltage and current, leading to more time to complete the charge. Including both types of chargers at EV charging stations accommodates the diverse needs of users. Fast chargers are cost-effective for emergency or quick charging, while slow chargers are more economical for long-duration charging.

According to the Ministry of Industry, Mine, and Trade, it is currently possible to register the vehicles listed in Table 1 through the government system [38]. Therefore, the calculations in this study are also based on these specific vehicles. The charging station under review includes 4 fast-charging nozzles for electric cars (three direct types with 50 kW capacity and one alternating type with 43 kW capacity). It also includes one slow AC charging nozzle for electric motorcycles with a capacity of 7.5 kW, and one AC nozzle for fuel cell bicycles with a hydrogen dispensing capacity of 0.2 kg per hour [39].

Table 1. Types of EVs Available in the Iranian Market [38].

Type of EV	Battery Capacity (kWh)	Number of EVs for Charging at the Station	Type of Charger
Luna GRE EV (JMEV Yi)	43.9	6	Fast AC-1
Sinogold – Tango 5	54.3	5	Fast DC-1
HONGQI - EQM5EV	56	10	Fast DC-2
Honda - ENY1	68.8	8	Fast DC-3
Audi - Q5	17.9	12	Fast AC-1
KMC EJ7	50.1	6	Fast DC-1

The electric motorcycles are the r3079 model, manufactured by Shenzhen Rooder Technology Co [40]. Each motorcycle has a battery capacity of 2.5 kWh. The station can charge up to three electric motorcycles per hour, enabling the charging of 36 motorcycles during its 12-hour daily operation.

The bicycles are the Alpha 2.0 model, manufactured by Pragma Industries, and require 2 liters of hydrogen for every 140 km travel [41]. According to the calculations, charging 69 bicycles per day requires 2 kg of hydrogen. Assuming hydrogen is supplied between 7 AM and 5 PM, this corresponds to a consumption rate of 0.2 kg of hydrogen per hour. The annual real interest rate is 23% [42], the project lifetime is set at 25 years [43], and the penalties per ton for CO_2, CO, SO_2, and NO_x emissions are \$3.1, \$57, \$560, and \$184, respectively [44]. The elevation above sea level is 1,191 meters. Figures 6 and 7 illustrate the monthly average solar radiation and wind speed for the station under review. It is noteworthy that the data in Figures 6 and 7 are 20-year averages obtained from NASA.

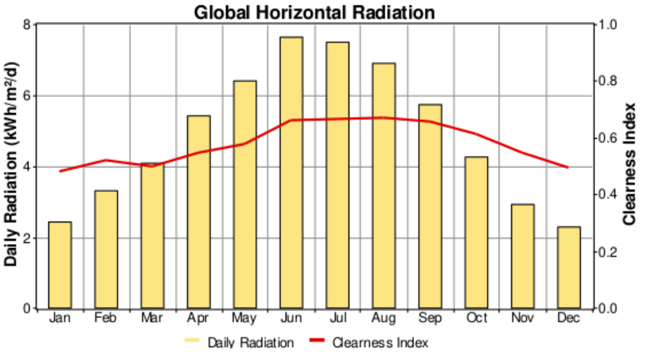


Fig. 6. Monthly average solar radiation

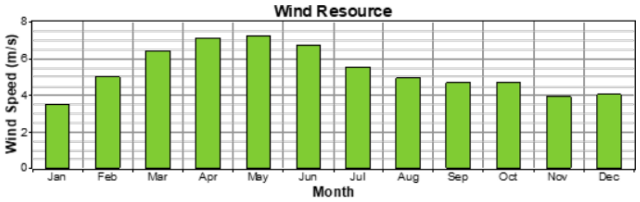
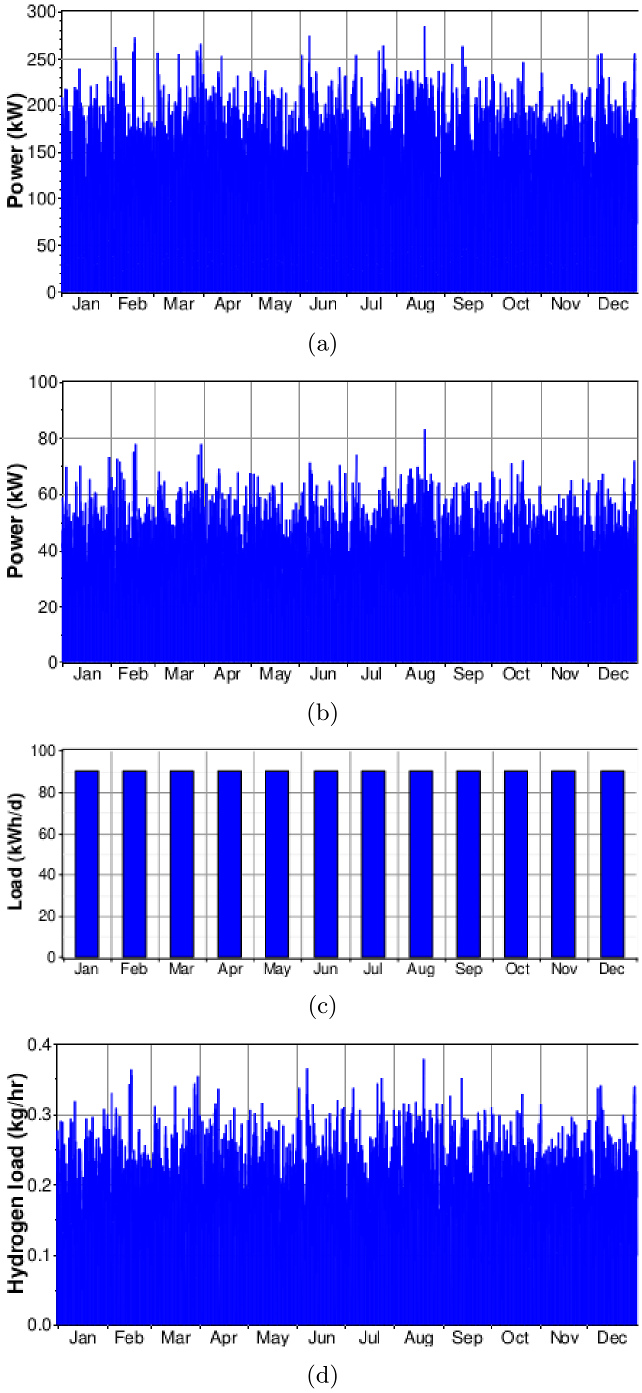


Fig. 7. Monthly average wind speed.

Figures 8a to 8c present the power requirement profile for the charging station, corresponding to DC fast charging, AC fast charging, and AC slow charging, respectively. Additionally, Figure 8d provides the annual hydrogen requirement profile.

Figure 9 presents the time-of-use tariff for electricity exchange with the national grid, showing off-peak, mid-peak, and peak periods, which vary in timing and pricing across different months. Meanwhile, the price of selling renewable electricity to the grid, due to its trading on the renewable electricity market, is considerably higher, even compared to the price of buying electricity from the grid during peak periods.

Table 2 provides the prices of the equipment used, technical information, and other relevant details.



(a)

(b)

(c)

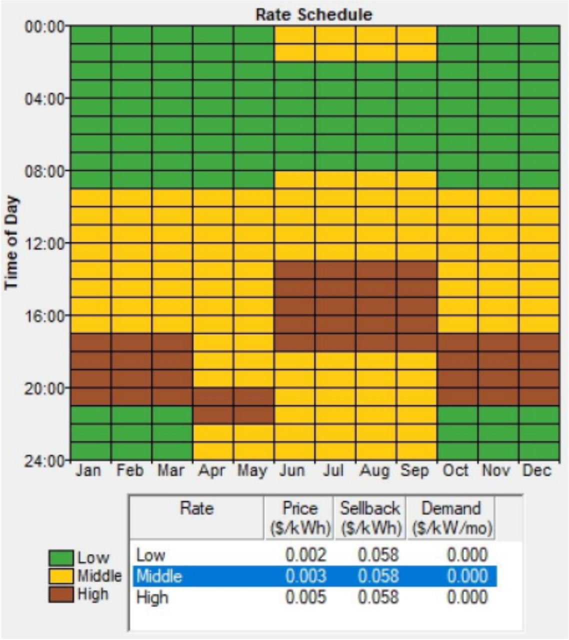
(d)

Fig. 8. Power requirement profile for the charging station (a) DC fast charging (b) AC fast charging (c) AC slow charging (d) hydrogen requirement.

5 Results

Table 3 presents the optimal economic system. The results indicate that the optimal system includes 800 kW of solar panels, 1000 kW of wind turbines, 700 kW of electrical converters, an 8 kW electrolyzer, and an 8 kg hydrogen storage tank. The dispatch strategy is cycle charging, and the national power grid is also utilized in the optimal system. The initial equipment purchase cost amounts to $1,232,400, with annual operating costs of – $71,019, resulting in a total net present cost of $925,367. The cost of electricity production is $0.087 per kWh, while the cost of hydrogen production is $292.12 per kg. The renewable energy fraction in this study is 96%.

The average price of solar and wind electricity globally in 2023 were $0.044 per kWh and $0.033 per kWh, respectively [45]. Additionally, the cost of producing wind or solar hydrogen in 2024 ranges between $1.5 to $4 per kg [46]. The reason the optimal price of renewable electricity and hydrogen produced in Iran is higher than global prices can be attributed to the relatively low cost of grid electricity and fossil fuels in Iran. Additionally, the high cost of electrolyzer technology in the country further contributes to this price difference. Moreover, the very low penalties for pollutants in Iran have made the use of grid electricity the best option.



Rate	Price ($/kWh)	Sellback ($/kWh)	Demand ($/kW/mo)
Low	0.002	0.058	0.000
Middle	0.003	0.058	0.000
High	0.005	0.058	0.000

Fig. 9. Time-of-use tariff for electricity exchange with the national grid.

Table 2. Simulated hybrid power plant information.

Component	Purchase ($)	Replacement ($)	Operating & Maintenance ($)	Data	Size of equipment
Wind Turbine Generic (1 kW) [47]	850	850	10	Lifetime: 20 year, Hub height: 17m	0-1000 kW
PV (1 kW) [48]	350	350	10	Lifetime: 25 year, Slope: Latitude, Azimuth: South	0-1000 kW
Converter (1 kW) [49]	138	138	10	Lifetime: 15 year, Efficiency: 90%	0-1000 kW
Electrolyzer (8 kW) [34]	2700	2700	3	Lifetime: 15 year, Efficiency: 85%	0-8 kW
Hydrogen Tank (8 kg) [34]	3100	3100	4	Lifetime: 25 year	0-8 kW
Grid [50]	-	-	-	CO_2: 632 gr/kWh, SO_2: 2.74 gr/kWh, NO_x: 1.34 gr/kWh	0-10000 kW

Table 3. Results of the Optimal Economic System

Configuration	PV (kW)	G1	Conv. (kW)	Elec. (kW)	H_2 Tank (kg)	Disp. Strgy	Grid (kW)	Initial Capital ($)	Operating cost ($)	Total NPC ($)	COE ($/kWh)	COH ($/kg)	Ren Frac.
	800	1000	700	8	8	CC	100000	1232400	−71019	925367	0.087	292124	0.96

Despite the higher costs, the development of renewable energy projects in Iran is of great importance due to their potential to reduce air pollution, enhance energy security, optimize the use of natural resources, foster technological advancement, create jobs, and promote sustainable development.

Figure 10 displays the revenue generation of the system over 25 years, indicating a profit of $346,428 at the end of the 25th year. The results reveal that in the 15th and 20th years, there will be a negative slope in the revenue graph due to the costs of replacing electrical converters and wind turbines. The reason for the positive costs in the 25th year is the salvage value (sale of usable equipment), which leads to the profitability of the hybrid system under review.

The sharp decline in the revenue graph in year 20 is due to the lifetime end of the wind turbines, which imposes a significant cost on the system. The reason for the increase in the slope of the graph in year 25 is attributed to the salvage cost of the equipment, which results from the sale of equipment that still has usability at the end of the project's lifetime. This positive cost, when added to the system, causes an upward slope in the graph in the final year of the project's lifetime.

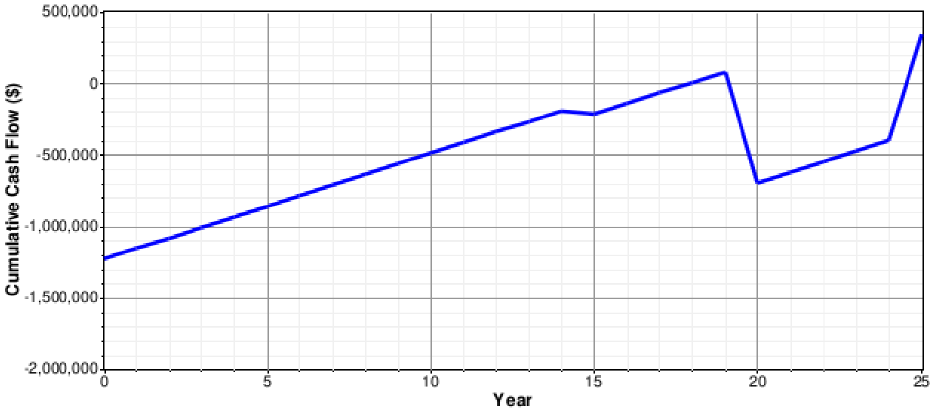


Fig. 10. Cost analysis of the system under review over the project's lifetime.

Figure 11 shows the electricity production by components of the hybrid system. It can be observed that out of the total annual production of 2,832,335 kWh, 45% is supplied by solar cells, 51% by wind turbines, and 4% by the national power grid. The figure also depicts the usage of the generated electricity. Of the total annual consumption of 2,482,740 kWh, 7% is allocated to one AC fast charging station, 25% to three DC fast charging stations, 1% to the AC slow charging station, 1% for electrolyzer consumption, and 66% is sold to the national power grid. About 5% of the electricity generated remains as surplus, which can be accounted for wiring losses and other connections. The figure also indicates that the highest monthly average solar power, wind power, and grid electricityare 180.3 kW (in August), 334.1 kW (in May), and 32.6 kW (in January), respectively. In the months of June and May, as we have the maximum wind speed (according to Figure 7) and the maximum solar radiation (according to Figure 6) respectively, grid electricity is not required to meet the system's energy demand, as 100% of the demand is supplied by renewable energy sources.

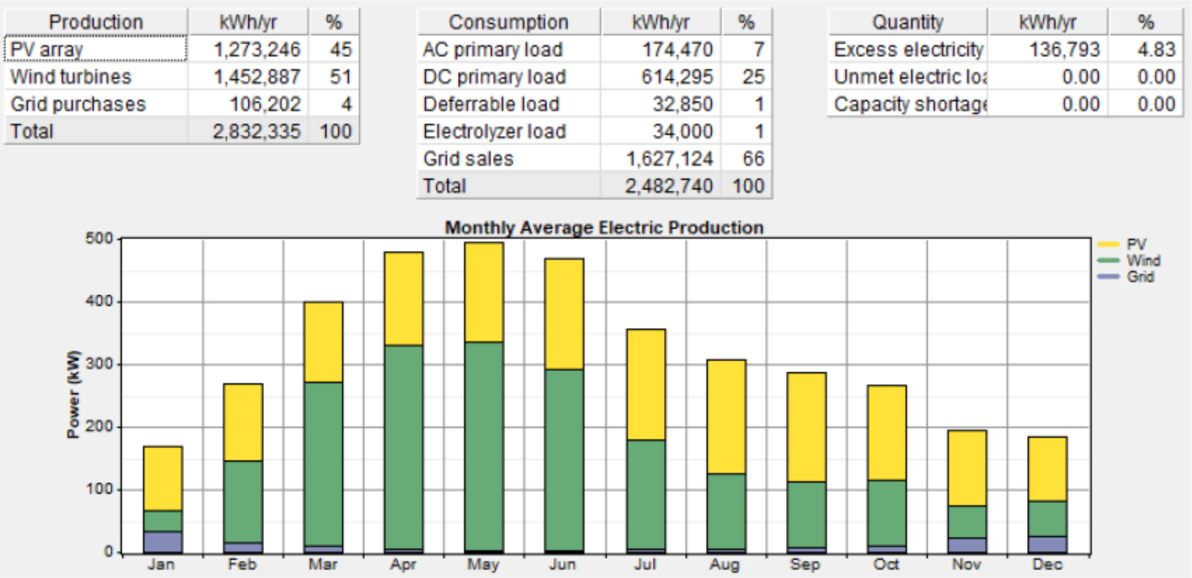
Figures 12a and 12b present the performance contours of the solar cells and wind turbines, respectively. The average output power of solar cells and wind turbines is 145 kW and 166 kW, respectively. The capacity factor for solar cells is 18.2%, while that of the wind turbines is is 16.6%, with operational hours of 4384 hours and 7191 hours per year, respectively. According to Figure 12, the highest levels of solar and wind power generation occurs during daylight hours.

Figures 13a and 13b illustrate the performance contours of the inverter and rectifier, respectively. The inverter has an average annual output of 209 kW with a capacity factor of 29.8%, while the rectifier produces an average of 6 kW annually, corresponding to a capacity factor of 0.9%. The inverter and rectifier are active for 7018 hours and 725 hours per year, respectively, during which they experience electrical losses of 203,026 kWh/year and 9,764 kWh/year.

Table 4 shows the monthly electricity exchange with the national grid during off-peak, mid-peak, and peak periods. The highest and lowest electricity purchases from the grid were 24,287 kWh in January and 1,940 kWh in May, respectively. Annually, a total of 106,202 kWh of electricity was purchased from the grid.

In January and May, with 46,106 kWh and 239,891 kWh, respectively, the lowest and highest amounts of electricity were sold to the grid. Throughout the year, a total of 1,627,124 kWh of electricity was sold to the national grid. Thus, according to Table 4, electricity sales to the national grid exceeded purchases in all 12 months of the year, resulting in a net annual sale of 1,520,922 kWh. The results also show that the highest electricity sales to the grid occurred during daylight hours, primarily during the mid-peak period. The peak and off-peak periods ranked second and third, respectively, in terms of the highest electricity sales to the grid.

The performance contour of the electrolyzer is shown in Figure 14. It has an average power output of 3.881 kW, consumes 34,000 kWh of energy annually, and operates for 4,926 hours per year, resulting in a capacity factor of 48.5%. The electrolyzer's maximum hydrogen production rate is 0.172 kg/hr, yielding an annual hydrogen production of 733 kg. Consequently, its energy consumption amounts to 46.4 kWh per kilogram of hydrogen produced.

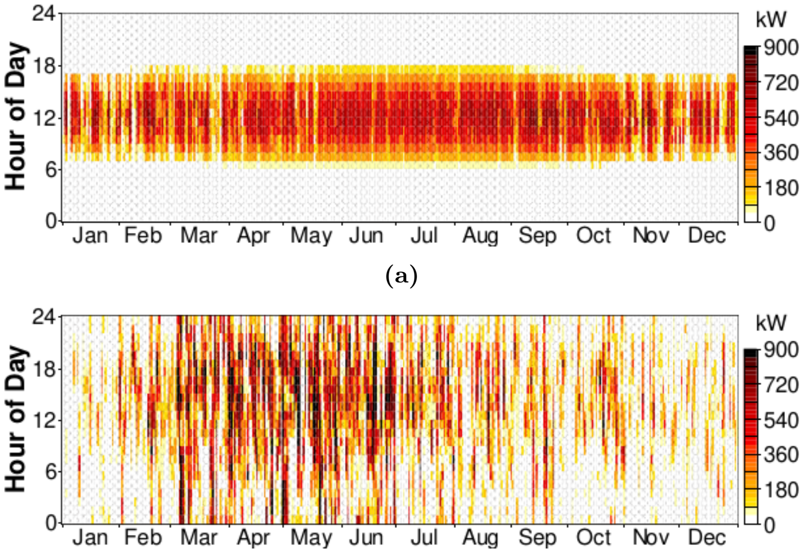


Production	kWh/yr	%
PV array	1,273,246	45
Wind turbines	1,452,887	51
Grid purchases	106,202	4
Total	2,832,335	100

Consumption	kWh/yr	%
AC primary load	174,470	7
DC primary load	614,295	25
Deferrable load	32,850	1
Electrolyzer load	34,000	1
Grid sales	1,627,124	66
Total	2,482,740	100

Quantity	kWh/yr	%
Excess electricity	136,793	4.83
Unmet electric lo	0.00	0.00
Capacity shortag	0.00	0.00

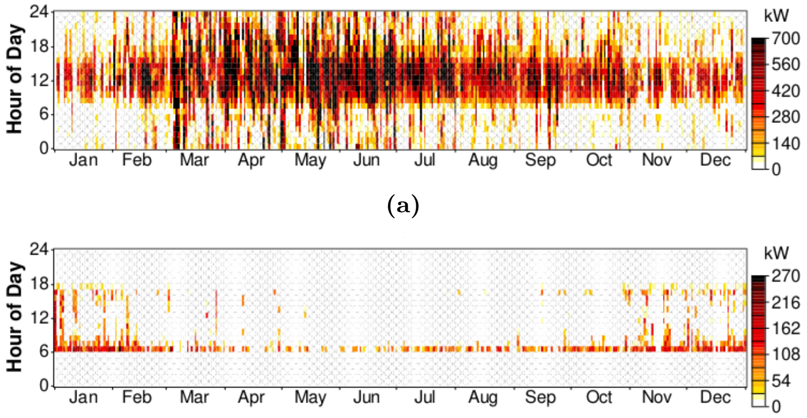
Fig. 11. Electricity production by components of the hybrid system.



(a)

(b)

Fig. 12. Performance contours (a) solar cells (b) wind turbines.



(a)

(b)

Fig. 13. Performance contours (a) inverter (b) rectifier.

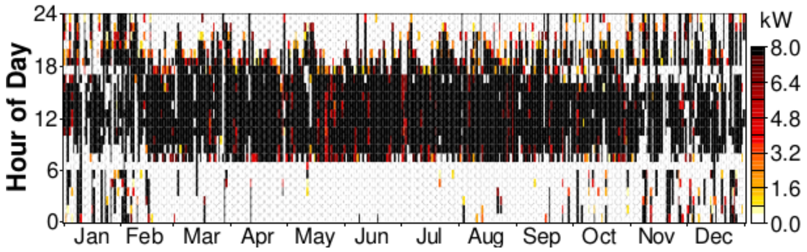


Fig. 14. Performance Contour of the electrolyzer.

Table 4. Electricity exchange with the national grid.

off-peak				mid-peak				peak			
Month	Energy purchased (kWh)	Energy sold (kWh)	Net purchases (kWh)	Month	Energy purchased (kWh)	Energy sold (kWh)	Net purchases (kWh)	Month	Energy purchased (kWh)	Energy sold (kWh)	Net purchases (kWh)
Jan	12566	4904	7661	Jan	9999	38355	−28356	Jan	1722	2846	−1124
Feb	7680	16028	−8348	Feb	2674	66102	−63429	Feb	183	14051	−13867
Mar	4709	68026	−63317	Mar	2612	85756	−83144	Mar	170	31869	−31700
Apr	1892	46215	−44323	Apr	1055	156326	−155272	Apr	8	18459	−18451
May	1551	57912	−56361	May	389	164421	−164032	May	0	17558	−17558
Jun	2195	21990	−19795	Jun	53	122362	−122309	Jun	37	68094	−68057
Jul	3685	14193	−10508	Jul	184	92550	−92366	Jul	155	54454	−54299
Aug	3579	9541	-5961	Aug	150	71958	−71808	Aug	275	45291	−45016
Sep	3821	12397	−8576	Sep	832	68150	−67317	Sep	998	34268	−33270
Oct	5942	17134	−11193	Oct	1517	75472	−73955	Oct	514	14454	−13940
Nov	8675	7700	974	Nov	6239	47493	−41253	Nov	1263	5248	−3985
Dec	10429	8440	1989	Dec	6998	40771	−33773	Dec	1451	6335	−4885
Annual	66724	284481	−217757	Annual	32702	1029716	−997014	Annual	6776	312927	−306151

The main pollutants of grid electricity are based on CO_2, SO_2, and NO_x. Therefore, other minor pollutants are excluded from the calculations and are listed as zero (very negligible) in Table 5. According to Table 2, it is also mentioned which types of pollutants are the main and major ones of the grid electricity. Given the sale of renewable electricity to the national grid, it is evident that emissions are negative, indicating the prevention of pollutant release. Based on the results, the system annually prevents the emission of 961,223 kg of CO_2, 4,167 kg of SO_2, and 2,038 kg of NO_x.

For the first time, this study presents an optimal combination of wind and solar renewable energy that successfully supplies 96% of the energy demand for EV charging stations. Additionally, simultaneously provision of energy for electric vehicle charging and hydrogen production for hydrogen-powered bicycles represents an innovation that has not yet been implemented in Iran. Furthermore, economic simulation, which account for the sale of excess electricity to the grid at updated prices and incorporates penalty mechanisms for pollutant emissions, increases the practical significance of the results for decision-makers.

Table 5. Pollutant Emissions Results of the Optimal System.

Pollutant	Emissions (kg/yr)
Carbon dioxide	−961223
Carbon monoxide	0
Unburned hydrocarbon	0
particulate matter	0
Sulfur dioxide	−4167
Nitrogen oxides	−2038

Regarding the necessity of this study, of which no similar example exists in Tehran and Iran, it should be mentioned that given the severe air pollution problem in Tehran, using renewable energies in EV charging stations can play an important role in reducing environmental pollution. This research which aims to reduce dependence on fossil fuels and move towards a carbon-free society, holds particular important in achieving the country's environmental and economic goals. Finally, it should be noted that with the growing adoption of electric vehicles, the development of appropriate charging infrastructure is essential. These considerations highlight that this research is both scientifically and practically innovative, offering applicable and effective solutions for delivering sustainable energy.

6 Suggestions for Future Works

The following four practical suggestions for future research are presented:

- Examining the impacts of using advanced technologies such as deep learning modeling or intelligent optimization algorithms on reducing costs and increasing the efficiency of energy and hydrogen production.
- Evaluating the connection of hybrid systems to smart grids and integrated load management to enhance stability and efficiency.
- Simulating and analyzing the system performance in different geographical regions with varying climate conditions and energy markets for higher adaptability and better planning.
- Studying structural and technological changes in electrolyzers to reduce energy consumption and hydrogen production costs.

These suggestions can help expand research and increase the efficiency and applicability of the present research.

7 Conclusion

The establishment of EV charging stations powered by renewable energy in Tehran not only helps to reduce pollution and improve citizens' quality of life but also contributes to sustainable development and the optimal use of energy resources. This initiative can be considered a significant step towards achieving the country's environmental and economic goals. Therefore, this study is the first to simulate the power supply of a new-generation EV charging station – comprising three separate lines (DC fast charging, AC fast charging, and AC slow charging) – using wind and solar renewable energy sources. Another innovation of this study is the simultaneous provision of a hydrogen load for new-generation hydrogen bicycles through the charging station's green hydrogen supply via an electrolyzer. To enable the sale of surplus electricity to the national grid, the system was designed for grid connectivity. Additionally, penalties for pollutant emissions were incorporated, and electricity sales were priced according to the green energy market's three time periods. These considerations enhance the practical relevance of the results for energy policymakers and investors, addressing a key scientific gap. Technical-economic-energy-environmental simulations were conducted using HOMER software, with 20-year average climate data from NASA. Key results of the optimal economic system include:

- The system includes 800 kW of solar panels, 1000 kW of wind turbines, 700 kW of electrical converters, an 8 kW electrolyzer, and an 8 kg hydrogen storage tank.
- The cost of electricity production is \$0.087 per kWh, and the cost of hydrogen production is \$292.1 per kg.
- Solar electricity production, wind electricity production, and net electricity sales to the grid are 1,273,246 kWh/year, 1,452,887 kWh/year, and 1,520,922 kWh/year, respectively.
- The total renewable energy fraction is 96%, with solar and wind contributing 45% and 51%, respectively.
- The produced hydrogen entails an electricity consumption of 46.4 kWh per kg.
- Annually, the system prevents the emission of over 961.2 tons of CO_2, about 4.2 tons of SO_2, and more than 2 tons of NO_x.

Nomenclature

A	Area swept by the blades (m^2)
A_{htank}	hydrogen tank autonomy (-)
AC	Alternative current (-)
BEV	Battery electric vehicle (-)
$C_{\text{A.O\&M}}$	Annual cost of components' operating and maintenance ($)
$C_{\text{A.cap}}$	Annual capital cost ($)
$C_{\text{A.rep}}$	Annual replacement cost ($)
$C_{\text{grid.energy}}$	Total annual cost of energy ($)
C_p	Wind generator capacity factor (-)
C_{power}	Grid power price ($/kWh)
C_{sellback}	Grid sellback price ($/kWh)
COE	Cost of energy ($/kWh)
d	Day (-)
DC	Direct current (-)
$E_{\text{net grid purchases}}$	Net grid power purchases (kWh)
E_s	Energy supplied during a year (kWh)
EV	Electric vehicle (-)
f	Annual inflation rate (%)
$f_{(v)}$	Weibull distribution (-)
f_{PV}	PV derating factor (%)
h	Hour(-)
HHV	High heating value (MJ/kg)
i	Real interest rate (%)
j	Data class numbers (-)
I_s	Amount of radiation used to rate the capacity of the PV array (kWh/m^2)
I_T	Global solar radiation incident of the surface of the PV array (kWh/m^2)
$L_{\text{prim.ave}}$	Average primary load (kWh/day)
LHV	Low heating value (MJ/kg)
n	Number of years (-)
NPC	Net present cost (-)
P_{PV}	Power production of the solar cells (kW)
P_{wind}	Mean power output of the wind turbine (kW)
PSO	Particle swarm optimization (-)
R	Size of the power converter (-)
SSA	Sparrow search algorithm (-)
v	Wind speed (m/s)
Y_{PV}	Installed capacity of the solar cells (kW)
Y_{htank}	Hydrogen tank rated capacity (kg)
	Greek symbols
η_{electrol}	Electrolyzer efficiency (%)
ρ	Air density (kg/m^3)
τ	Analysis time (1 year)

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